AN EVALUATION OF A NUCLEAR POWER PLANT FOR A LARGE SURFACE EFFECT SHIP

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ABSTRACT

Promising high performance ships of the future such as the Surface Effect Ship (SES) suffer from the fact that their range is limited. A nuclear propulsion plant could solve this problem, if it could be made light enough to satisfy the propulsion plant weight "envelope" of the SES. In addition, any candidate power plant must be safe, maintainable, controllable, operable, and affordable in the ocean environment. Although present Naval Pressurized Water Reactors meet the latter conditions, they are too heavy for the SES.

An allowable range for propulsion plant weight for a nominal 12,000 ton displacement SES is discussed. Westinghouse has suggested a propulsion plant concept that could possibly satisfy the above requirements. It consists of a High Temperature Helium cooled reactor in a Direct Brayton Cycle, with all power generating equipment being inside the containment. An alternative concept (Indirect Brayton Cycle) is proposed with only the reactor and a simplified primary loop inside the containment.

The two concepts are compared and possible advantages as well as disadvantages of the modified concept are discussed. Based on the comparison, the Indirect Brayton Cycle is concluded to be preferrable to the Direct Brayton Cycle for this particular SES application. While the modified concept is heavier and less efficient, it has the advantage of being more maintainable, and hopefully more reliable.

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Chapter 1

INTRODUCTION

1.1 Background

The nuclear age of ship propulsion began over 21 years ago, when the first nuclear powered submarine, the U.S.S. NAUTILUS (SSN-571), put to sea. Its use has progressed to the point where now nuclear power is used as a source of propulsive and auxiliary power in well over 200 Naval vessels worldwide. The predominant power plant in these vessels is the Pressurized Water Reactor (PWR), which tends to be very heavy. If one defines the propulsion plant specific weight to be the total power plant weight divided by the installed shaft horsepower (SHP), then these Naval PWR's are estimated to have a specific weight on the order of 100 lbs/shp (B4).

1.2 Future Navy

In recent years various high performance ships, including Hydrofoils, Air Cushion Vehicles (ACV) and Surface Effect Ships (SES), have been under development and study as possible additions to the Navy of the future. One characteristic that is common to each of the above, is the ability to attain high speeds, when compared to present day ships. The price that must be paid for this high speed is a high installed power level, with the resulting high fuel consumption and short range. The combination of rapidly rising fuel costs and limited range serve to reduce the military worth of these vessels.

1.3 Light Weight Nuclear Power Plant

If a nuclear propulsion plant was capable of being utilized by a high performance ship, the potential advantages would be immense. The combination of high speed and payload carrying capability coupled with an essentially unlimited range (limited only by crew endurance), would constitute a potent weapon system for military use, and a possible boon to the commercial transportation industry. Unfortunately the fraction of the total ship weight that can be devoted to the propulsion plant is limited, and for the case of the SES would require a propulsion plant (depending on ship size, payload, mission, speed etc.) with a specific weight of roughly 15 lbs/shp (B4). This very low specific weight rules out present PWR's as a possible candidate, and even some of the integrated PWR's such as Babcock and Wilcox Consolidated Nuclear Steam Generator (CNSG) or Combustion Engineerings Unified Modular Plant (UNIMOD). These plants have lower specific weights (M1), than present estimates of Naval PWR's, but are still not low enough to be used on any of the high performance ships mentioned above.

In 1974 the Office of Naval Research (ONR) sponsored a workshop specifically concerned with light weight nuclear power plants (R4). This workshop was predominantly aimed at low specific weight power plants for ship propulsion. One such concept was presented by a group from Westinghouse Astronuclear Laboratory (WANL). Their concept was a departure from the proven PWR that is the mainstay of the

nuclear Navy. It did meet or exceed the desired specific weight goal, but depended on several long range development programs for a successful demonstration of feasibility. Westinghouse sought to continue development of their concept, but received no funding. At present, with the possible exception of Admiral Rickover's Naval Reactors group, there is no Navy funded work being done on the development of low specific weight nuclear power plants (S3).

1.4 Objectives

It is the intent of this thesis to take a critical look at the WANL concept, with a discussion of its advantages and disadvantages as a candidate power plant for a large SES. A modified concept (utilizing WANL as a base) is proposed that addresses some of the areas of technical risk associated with the Westinghouse baseline plant. The relative advantages and disadvantages of this modified plant when compared with the WANL baseline are also discussed. In addition, the author makes some conclusions concerning the practicality of this modified design as a candidate power plant for a Surface Effect Ship.

Chapter 2

SES SHIP REQUIREMENTS

2.1 Description

In order to discuss a candidate propulsion system for a Surface Effect Ship, one should discuss the SES itself. Unlike conventional monohulls which are totally supported by the buoyant force of the water, the SES is a "Captured Air Bubble" (CAB) vehicle with about 90-95% of its weight supported by a cushion of air. The air is at low pressure and is trapped between the rigid sidehulls, and flexible bow and stern seals.

2.2 Powering

From a powering standpoint the installed power level is proportional to the total drag on the ship and the design speed. Basically the effective horsepower (EHP), that amount of power that must be delivered to the water to move the ship at the desired speed, is defined as

$$EHP = \frac{RV}{550} \quad (HP), \tag{2.1}$$

where R is the total resistance to the motion of the ship in (lb_f), V is the ship speed in (fps) and 550 is the conversion factor to give horsepower. This is not the installed shaft horsepower (SHP), but is the power required if the total propulsive system were 100% effective.

In order to account for inefficiencies in the power transmission system, one defines a propulsive coefficient (PC) which is the product of the propulsor efficiency

(the relative ability of the propulsor to transmit power to the water), and other component efficiencies such as shafting, reduction gears, etc.. For propellers the efficiency depends on many factors which basically include its design (number of blades, pitch, blade area ratios, etc.), the RPM of the shaft, and hull interaction effects. A typical PC for a monohull might be about .65. The total power plant installed horsepower (SHP) is then defined as,

$$SHP = \frac{EHP}{PC}. \tag{2.2}$$

The resistance or drag on a conventional ship is decomposed into two components, the frictional drag (function of ship Reynolds number) and residuary resistance which combines wave making resistance, free surface effects and others not directly attributable to friction. In the case of a SES, the picture becomes more complex. There are many more components to the total drag, including:

1. Cushion wave making drag
2. Sidehull drag
    a. Wave making
    b. Friction drag
    c. Form drag
3. Aerodynamic drag
4. Momentum drag
5. Seal drag
    a. Wave making
    b. Friction
    c. Rough water

The major contributors to the total drag are cushion wave making, sidehull friction, and the combined effects of seal drag. In general, at SES cruising speeds (typically 50-100 knots), the SES has a much lower total drag than a conventional ship would have. It is difficult to make a comparison such as this, because monohulls are limited by present technology to maximum speeds somewhere between 30 and 40 knots.

2.3 Important Design Parameters

There are several ship parameters peculiar to the SES that have a significant impact on the final installed power level for a given displacement and speed. These include:

1. The cushion length to beam ratio (L_c/B_c). This affects wave drag and frictional drag.
2. The cushion density $W/\sqrt{A_c}$ (lbs/ft^3) where A_c is the cushion area and W is the displacement divided by the cushion area (lbs/ft^2). A high cushion density suggests a compact ship.
3. Weight or displacement. As weight increases the power to attain a given speed increases.
4. Propulsors. These are currently limited to waterjets or propellers. The propellers are probably super cavitating, either submerged or semi-submerged.
5. Lift power requirement. This depends on the cushion pressure P_c (which is related to cushion density) and the allowable leakage past bow and stern seals. The

lift fans are either axial, cenrifugal or mixed flow, and can be designed to provide ride control in a seaway.

Although this description of the SES is admittedly simplified, it will suffice for the purpose of this work. Figure 2.1 is an artist's conception of the 3KSES, which is to be a weaponized test platform, and is being designed and built for the Navy by Rohr Industries.

2.4 Baseline SES

The SES chosen as the baseline ship for the purposes of the power plant evaluation, was the output of a design project at M.I.T. (C2). The ship was sized for a particular mission, carrying a specified payload with a fixed payload weight. The total installed power was determined to be 462,000 SHP (including a 10% margin), for this high L_c/B_c SES. The full load displacement is about 11,700 tons which includes 15% of the lightship (full load displacement minus variable loads) as a design margin.

Based on this particular SES, limits were placed on the allowable range of the propulsion plant specific weight. This was done by determining the weight that would be required for ship structure, and all other items, not related to propulsion. Then the allowable weight for the propulsion plant was determined, essentially as the difference between the full load displacement and the sum of margin, structural weight, loads, auxiliaries, outfit and furnishings, and payload. Figure 2.2 illustrates this range. The lower curve represents

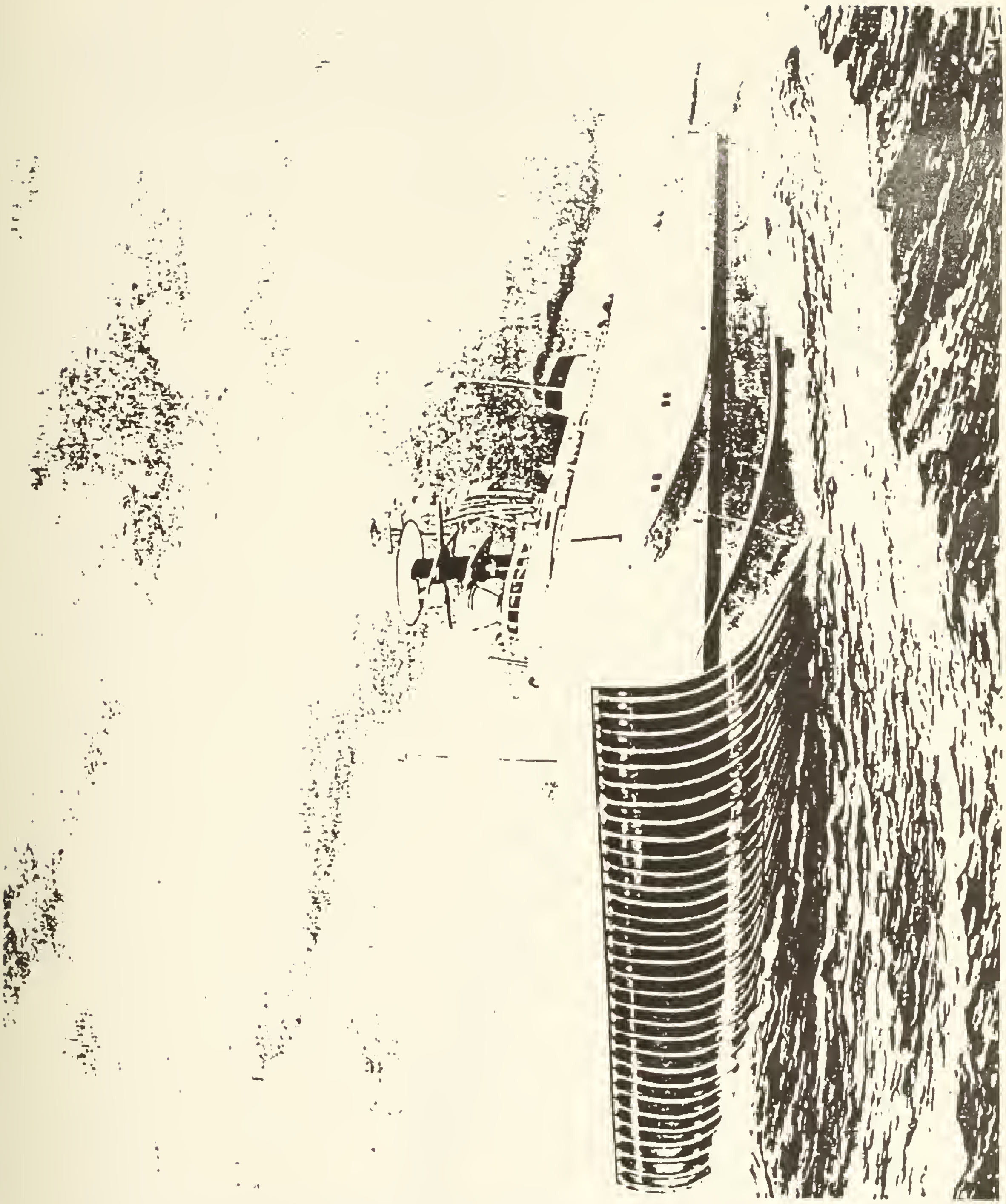
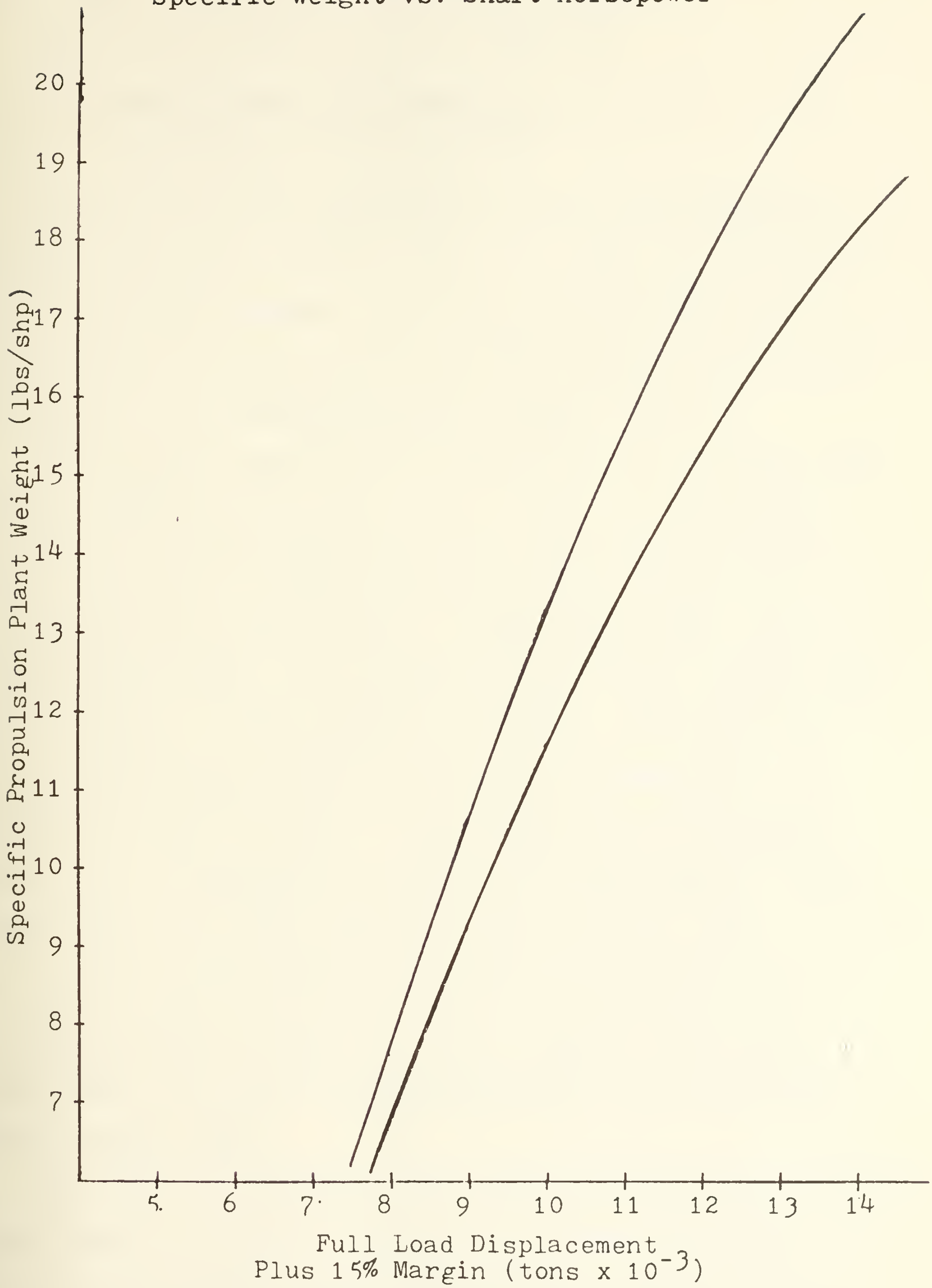


FIGURE 2.1
The U.S. Navy's 3KSES

FIGURE 2.2

Specific weight vs. Shaft Horsepower



the design goal. The upper curve indicates the permissible upper limit (design goal + 15% design margin).

These limits for the baseline SES are:

Design goal - 14.8 lbs/shp,

Upper limit - 17.0 lbs/shp.

Since at the time the design project was undertaken, the final ship size was not fixed, the range is plotted as a function of displacement. One can consider this range, a "design lane" in which the power plant designer must remain in order for the resultant ship to remain feasible.

This "design lane" is only valid for this baseline SES concept. The assumptions include a fixed payload weight, a specified mission, predetermined structural weight fraction, a fixed speed and L_c/B_c ratio. Given these fixed inputs, at a lower displacement, the fraction of the total displacement that is devoted to the payload is higher. This means that the available weight fraction that can be devoted to the propulsion plant is lower. This results in a considerably lower value of permissible propulsion plant specific weight (even though the installed horsepower is also lower). If one were to arbitrarily choose 15 lbs/shp as a design goal for conceptual design, Figure 2.2 would suggest that there is a lower limit to the full load displacement for this fixed payload weight case.

The design displacement was chosen by assuming a specific weight limit of about 15 lbs/shp, even though the WANL estimates for larger plants suggested the weight would be lighter.

2.5 Weight Definitions

In order to provide a common basis for further discussion on what is considered part of the propulsion plant weight, an excerpt from the U.S. Navy Ship Work Breakdown Structure (SWBS) is included in Figure 2.3. The propulsion plant weight for a SES is defined to include all appropriate items in group 200, and item 567. In addition item 298 - Propulsion Plant Operating Fluids - is to include the water in the inlet and outlet ducting of the main seawater heat exchangers as well as in the waterjet propulsion system.

2.6 Discussion

Different ships will have different limits placed on the propulsion plant specific weight depending on all the above considerations, and each ship should be considered on a case by case basis. Should a propulsion plant design fall outside of the designlane, several things could happen. First, if it was below the design goal (i.e. lighter than anticipated) either more payload could be carried at the same displacement, or the ship could get smaller. In either case the final result would be achieved through an iterative design process. The second possibility is that it exceeds the design lane, or is some predetermined fraction above the design goal. This would result in either a larger ship, or a possible easing of some of the design requirements such as payload weight and volume, speed, mission duration, etc.. The effect would be one of either moving the propulsion plant into the design lane, or moving the design lane to fit the particular plant.

GROUP 200 PROPULSION PLANT

200	Propulsion plant, general
201	General arrangement – propulsion drawings
202	Automated ship control systems
210	Energy generating system (nuclear)
211	(Reserved)
212	Nuclear steam generator
213	Reactors
214	Reactor coolant system
215	Reactor coolant service system
216	Reactor plant auxiliary systems
217	Nuclear power control and instrumentation
218	Radiation shielding (primary)
219	Radiation shielding (secondary)
230	Propulsion units
231	Propulsion steam turbines
232	Propulsion steam engines
233	Propulsion internal combustion engines
234	Propulsion gas turbines
235	Electric propulsion
236	Self-contained propulsion systems
237	Auxiliary propulsion devices
238	Secondary propulsion (submarines)
239	Emergency propulsion (submarines)
240	Transmission and propulsor systems
241	Propulsion reduction gears
242	Propulsion clutches and couplings
243	Propulsion shafting
244	Propulsion shaft bearings
245	Propulsors
246	Propulsor shrouds and ducts
247	Water jet propulsors
250	Propulsion support sys. (except fuel and lube oil)
251	Combustion air system
252	Propulsion control system
253	Main steam piping system
254	Condensers and air ejectors
255	Feed and condensate system
256	Circulating and cooling sea water system
259	Uptakes (inner casing)
260	Propulsion support systems (fuel and lube oil)
261	Fuel service system
262	Main propulsion lube oil system
263	Shaft lube oil system (submarines)
264	Lube oil fill, transfer, and purification
290	Special purpose systems
298	Propulsion plant operating fluids
299	Propulsion plant repair parts and special tools
567	Lift Fans

FIGURE 2.3

From a ship design standpoint, the determination of the propulsion plant size is more complex than the above analysis would lead one to believe. Most conventional ships, for instance, are weight and/or volume limited. The approach taken above suggests that the SES is only weight limited, which within reasonable limits is found to be the case (F1). Most conventional warships are volume limited, meaning that the volume of the individual elements of the final ship, and not necessarily the weight of those elements has the larger impact on the ship design process. Other considerations that warrant investigation when considering the impact of a nuclear propulsion plant on a ship include:

1. "Ruggedness", a term that can be used to denote the ability to operate reliably under continuous accelerations, as well as shock and vibrations that are transmitted by the ship structure.
2. Collision and missile resistant - This has an impact on the total nuclear system design, as well as necessitating additional ship structure in the form of collision bulkheads and ballistic protection.
3. The system should be fail-safe in the face of possible fire, flooding, grounding or sinking.
4. It is desirable that the system can be shut down by the operator in case the automatic controls suffer an interruption due to any of the above mentioned conditions.
5. The system must operate reliably and safely under

possibly frequent and rapid changes in power level. This is especially important for Naval ships.

6. There must be sufficient biological shielding to limit the exposure of the crew and other personnel to specified radiation dose limits.
7. Cost - This includes development cost, capital costs and operation and maintenance expenses.

Whereas the first six of the above can usually be satisified, the cost to develop the technology may be prohibitive. The impact of all of these items on the power plant weight must not be overlooked. The above requirements tend to make reactor systems heavy, and occupy large volumes. Although the Naval PWR meets all of the above requirements, to one degree or another, it is also much too heavy to be used on a high performance ship.

Chapter 3

WESTINGHOUSE BASELINE POWER PLANT

3.1 Background

In 1973 a team of scientists and engineers from Westinghouse and Los Alamos Scientific Laboratory began a study of an advanced light weight reactor system for ship propulsion (J1). The approach was to choose a demanding application and perform an in depth investigation with the following objectives:

1. Is a nuclear power plant, suited to such an application, feasible?
2. Does the basic technology exist to initiate a development and demonstration program?
3. Where problems are identified, can at least one engineering solution be identified?

The specific plant size chosen was a 140,000 SHP rating judged suitable for a 2,000 ton SES in the 1990 time frame. The system design requirements are indicated in Figure 3.1. WANL concluded that the power plant specific weight requirement for the SES was limited to about 15 lbs/shp. Their definition of the specific weight did not include allowances for lift fans or propulsors, so in that respect differs from the definition given in Chapter 2.

Although several systems were studied, the one selected was a closed Brayton cycle, with a Helium cooled, graphite moderated reactor as the heat source. In the basic scheme the power turbines were to drive super conducting generators

Application	2000 Long Ton SES
Mission Duration	6 Months Maximum Each Mission
Life - Design	10,000 Full Power Hours
- Demo	4,000 Full Power Hours
Output Shaft Power	140,000 HP
Maximum Specific Weight	15 Lb. per HP
Load Characteristics	Capability to Accept Both Fixed and Variable Speed Loads
Load Transients	Up to $\pm$ 3% of Full Power per Second over the Range of 25 to 100% Power
Safety	Comply with the Intent of 10 CFR 50
Shielding	4π Shielding
	Personnel Dose Less than 5000 mr/yr at Duty Stations (10 mr/hr at 20 ft from Reactor Centerline at Full Power)
Collision	The Containment must be Capable of withstanding a 30 Knot Collision without Breaching
Height	40 Ft. Maximum
Seawater Temperature	85°F
Air Temperature	100°F

FIGURE 3.1
Propulsion Plant Design Criteria

which supplied current to drive the lift fans and propulsors.

3.2 Power Plant Description

As indicated above the system is a closed Brayton cycle, using Helium as the working fluid. The core is a graphite moderated, epithermal spectrum reactor, with TRISO type beads in extruded graphite fuel elements. Some of the additional design considerations used to get a low space and weight system include:

1. The fuel is essentially all fissile.
2. Reactivity control is provided with rotating control drums in an efficient reflector.
3. The shield utilizes expensive materials and sophisticated design methods.
4. The reactor coolant system is very compact.
5. The reactor containment is engineered around the reactor coolant loops.
6. Refueling and major refurbishment is accomplished in a shore facility.

The system has a containment that looks like an inverted "T", with overall dimensions of 32 ft. long, 18 ft. wide and 34 ft. high. There are several auxiliary systems whose estimated volume is about 11,700 ft.^{3}. Three of the more important ones are:

1. The Fission Product Cleanup system which consists of molecular sieves and cryogenic charcoal beds. These are used to reduce the activity in the primary system.
2. Two storage volumes which can store Helium from the

charcoal bed, and also act as part of the inventory control/power level control scheme.

3. The emergency cooling system which functions without external power and transfers heat to ambient air through heat exchangers.

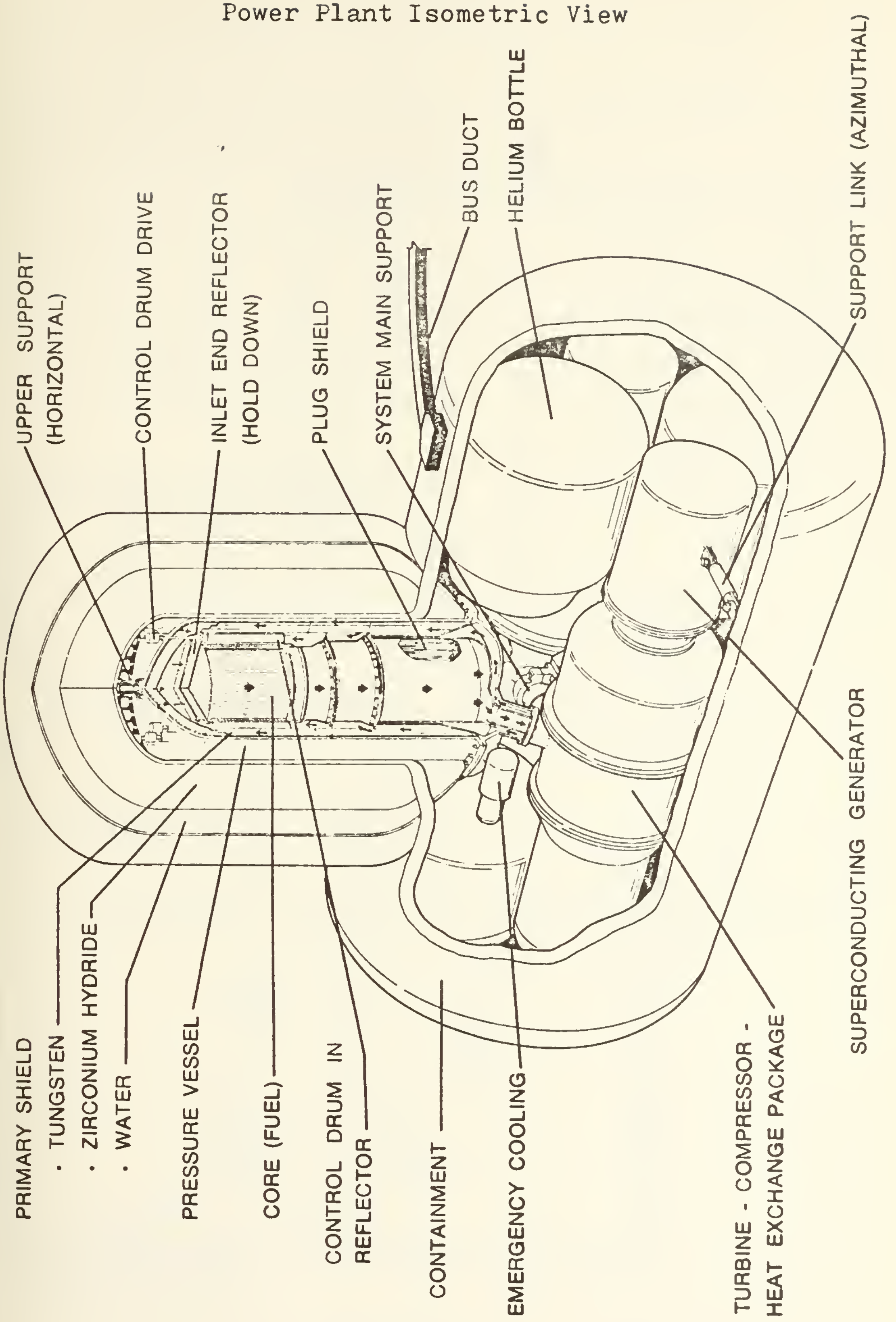
Figure 3.2 is a cut away view of the inverted "T" reactor configuration. The upper portion contains the reactor vessel and primary shield. The lower portion contains two Turbine - Compressor - Heat exchanger (T-C-Hx) modules each rated at 70,000 SHP. In addition the lower containment contains superconducting generators attached to each power turbine, the two Helium storage bottles, emergency cooling system, fission product cleanup system, the reactor and related systems support structure, and secondary shielding. Figure 3.3 is a schematic of one of the two identical power plant loops.

3.3 Reactor Core

Since 1962, Westinghouse has manufactured and tested nuclear rocket fuel elements and reactors in the Nuclear Rocket Vehicle Application (NERVA) Program (T4). The nuclear rocket program sought to develop gas cooled reactor cores of very high temperature (4000° F) and short lifetimes (less than 10 hours), using very corrosive Hydrogen gas which was both the coolant and the rocket propellant. Using the technology and design tools developed in the many years in the NERVA program, as well as the USAF Nuclear Extended Range Aircraft (NuERA) studies, WANL designed a high power density

FIGURE 3.2

Power Plant Isometric View



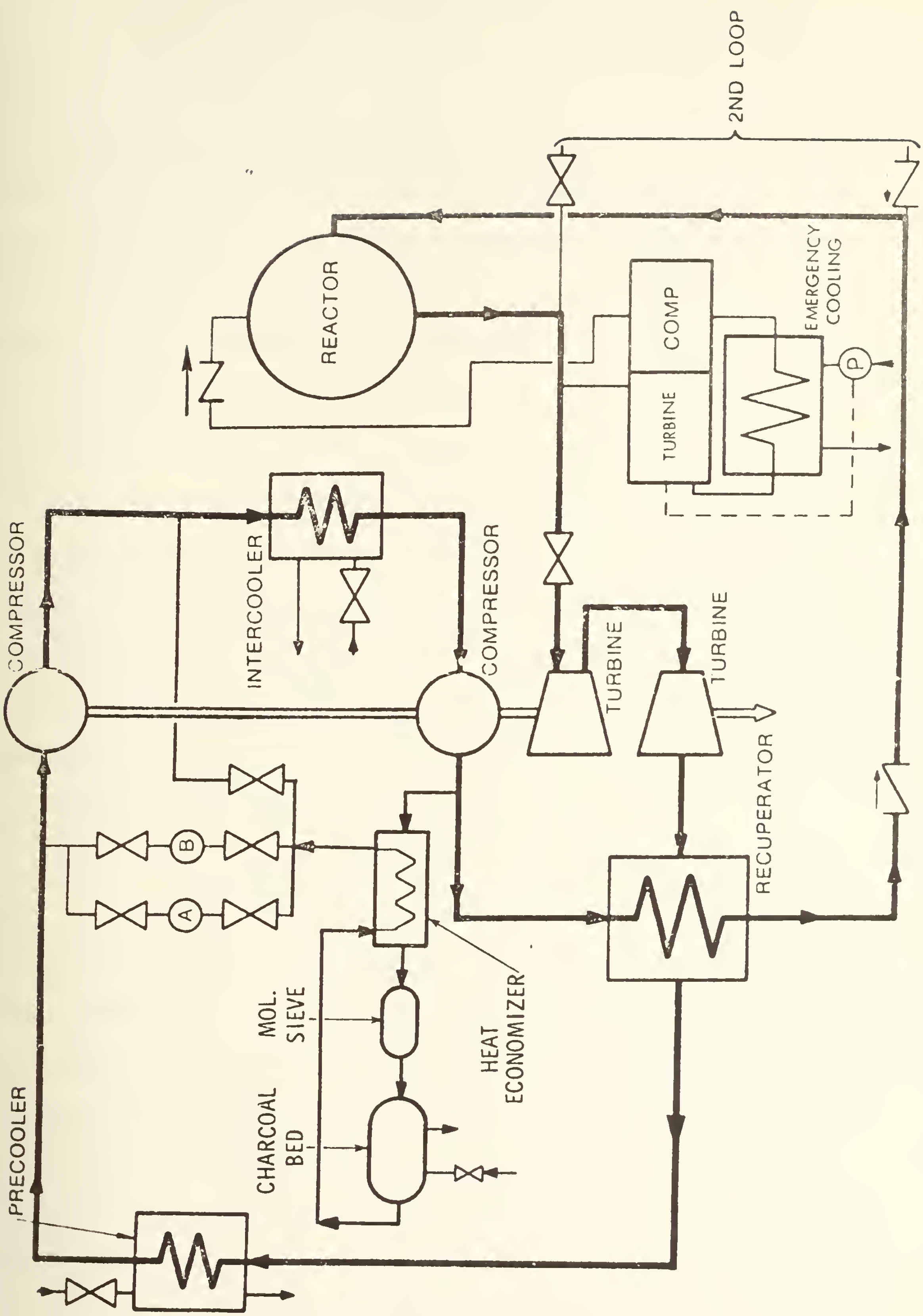


FIGURE 3.3
Power Plant Flow Diagram

core that was expected to have a long lifetime.

The baseline core is rated at 300 MW_t with a power density of 262 KW/liter. This compared to about 6 KW/liter for the Ft. St. Vrain HTGR, and about 40-70 KW/liter for proposed commercial PWR's for ship propulsion (M1). The fuel elements consist of high volumetric efficiency TRISO like beads, in a graphite binder, with 7 coolant holes per element. The elements are hexagonal with 3/4 inch across the flats and are about 45 inches long. The reference core is annular, with a central island of 3 rotating control drums which are used for long term reactivity control. Surrounding the core are control drums to maintain short term reactivity control. Each of the 24 peripheral control drums in the reference design contains B_4C. In addition to the central island, lifetime reactivity control is also maintained by a burnable Europium poison. The lifetime control reactivity requirements are indicated in Figure 3.4.

The core is zoned to achieve flux shaping and extend core life. The maximum Uranium loading is about 400 mg/cc, and the maximum burnup is 50% FIMA. The average burnup for the 10,000 EFPH core is about 38% FIMA. Because of the relatively low average Helium exit gas temperature of 1700° F (compared with the NERVA series cores, and the use of a non-corrosive gas (Helium vs. Hydrogen), there is a logical reason for expecting longer core life for this design. WANL concludes that exit temperatures of 1700° F can be obtained for 10,000 hours within the desired core volume with currently available

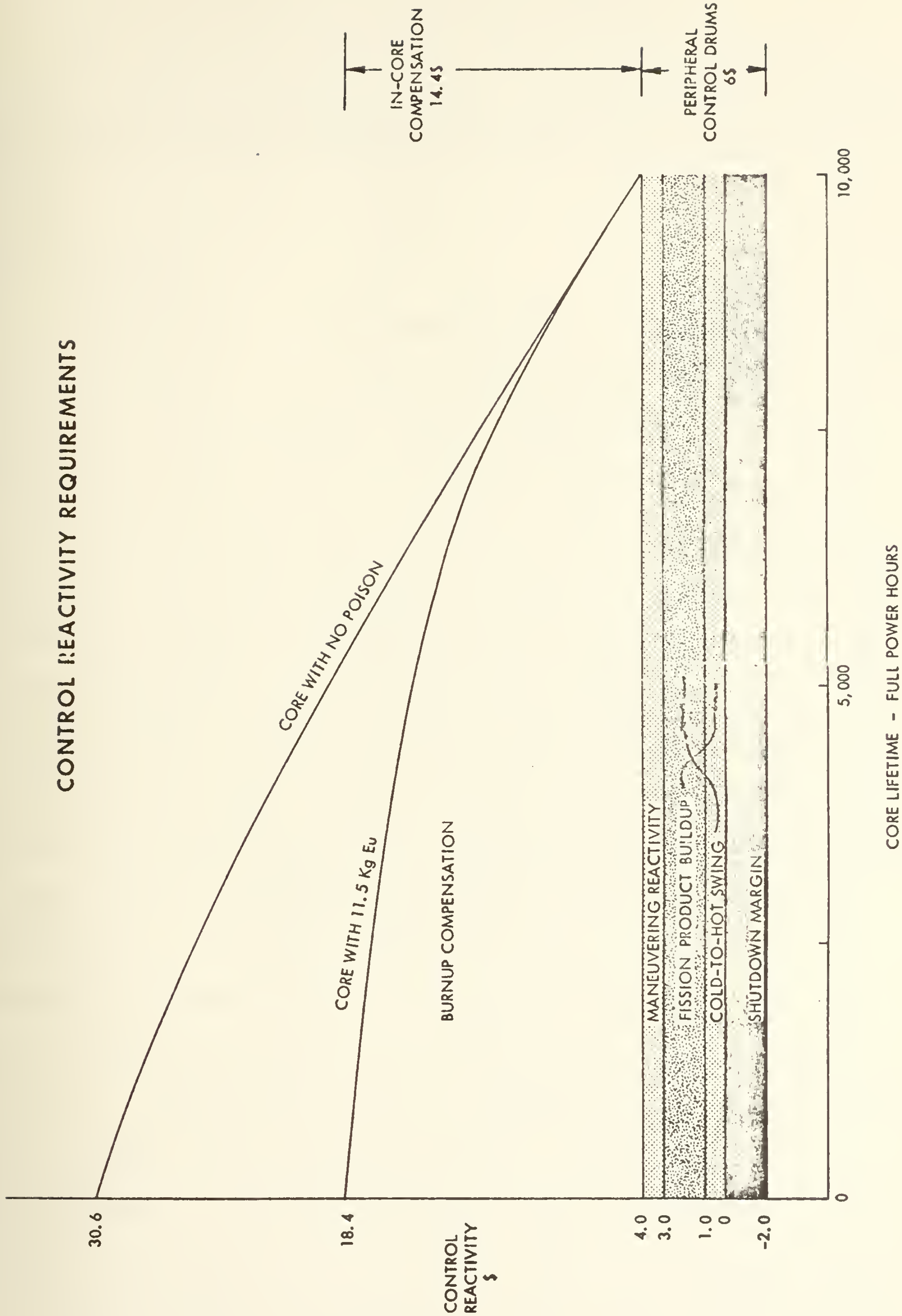

CONTROL REACTIVITY REQUIREMENTS
CORE WITH NO POISON
CORE WITH 11.5 Kg Eu
BURNUP COMPENSATION
MANEUVERING REACTIVITY
FISSION PRODUCT BUILDUP
COLD-TO-HOT SWING
SHUTDOWN MARGIN
IN-CORE COMPENSATION 14.4$
PERIPHERAL CONTROL DRUMS 6$
30.6
18.4
CONTROL REACTIVITY $
4.0
3.0
1.0
0
-2.0
0
5,000
10,000
CORE LIFETIME - FULL POWER HOURS

FIGURE 3.4

TRISO fissile particle coating technology (T4).

The core has a relatively low C/U ratio of about 70. It has lateral constraints which allow for thermal expansion and the core itself rests on a cooled (inlet Helium) support plate.

3.4 Control

Power control is accomplished by a combination of Helium inventory control, and reactivity control. The goal is to maintain constant reactor outlet temperature while varying Helium flow rate. In the inventory control scheme, Helium at high pressure is bled from the system to an intermediate pressure reservoir when power reduction is called for. When there is a demand for higher power, the intermediate reservoir supplies Helium to the low pressure compressor inlet. The storage volume pressure is always lower than the system high pressure, but higher than the system low pressure. Short term reactivity control is obtained by rotating the peripheral control drums, increasing reactivity for increased power demands and vice versa. Figure 3.5 is a diagram of the integrated control system. It should be pointed out that the above mentioned schemes are not the only possible means of control. Power control can be accomplished by turbine bypass flow to name just one method (G1). Reactivity control could be performed by more conventional control rods, which could reduce the overall reactor volume (T2). An optimal choice of methods would be determined during a more detailed design phase, which because of a lack of outside funding, Westinghouse

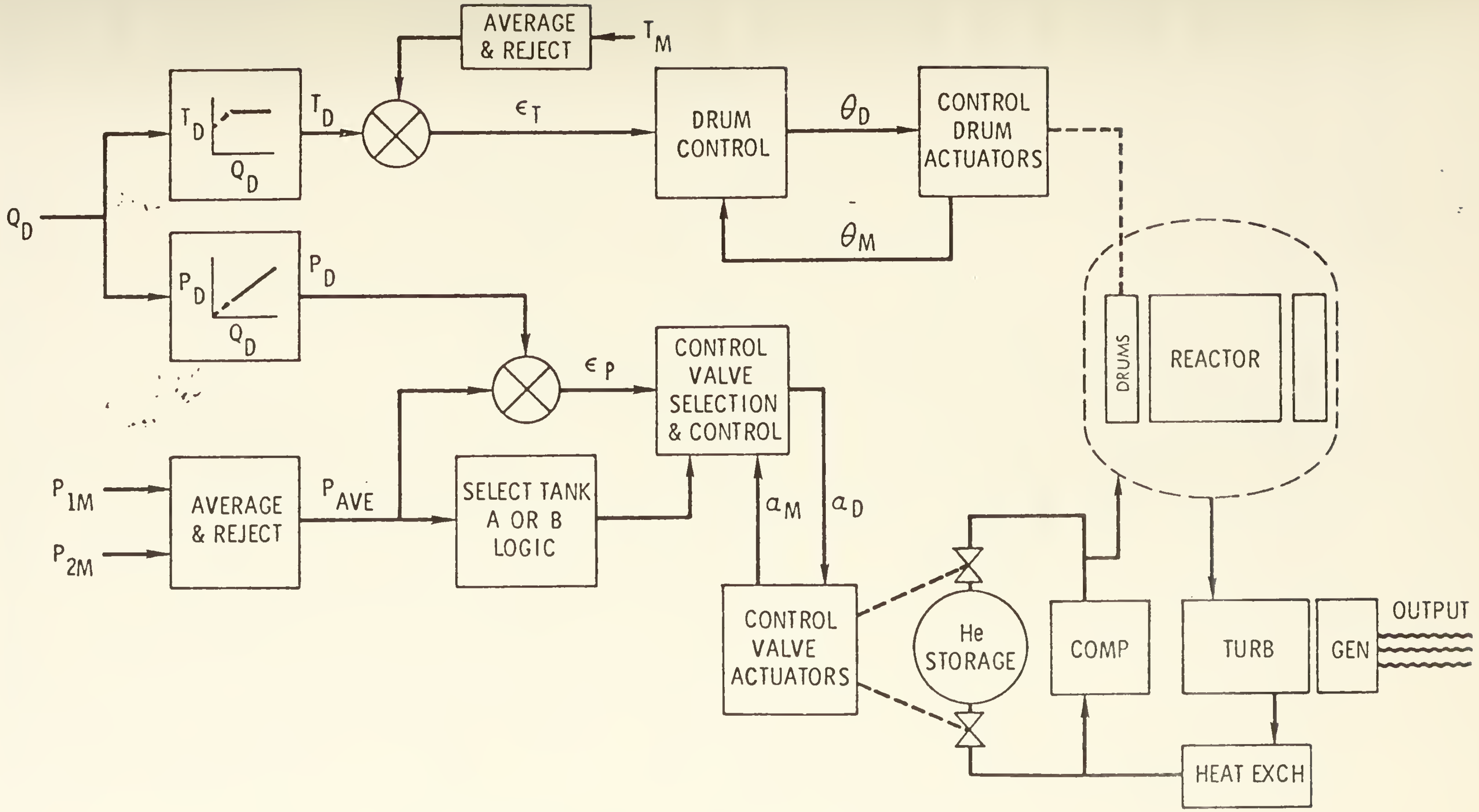


FIGURE 3.5
Proposed Plant Control Scheme

has not initiated.

3.5 Shield Design

The shielding design made extensive use of the techniques developed in NuERA. The core is surrounded by the combination Beryllium reflector and B_4C absorber in the control drums. External to that is a layer of Tungsten (γ shield) and the reactor pressure vessel. There is a small gap between the pressure vessel and containment vessel. Outside the containment, inside the shield tank is a layer of borated Zirconium Hydride, then a sheet of Boral, and then borated water. The design approach was to attempt to have an infinitely layered shield, in which there would be both neutron and gamma ray shielding materials. The shield was designed so that gamma rays produced in the shielding due to fast neutron reactions, would be rapidly attenuated. The methods used in the design procedure included a multivariate regression analysis and the use of expensive shield materials. This sophisticated shield design was necessary in order to achieve a relatively low weight while providing adequate biological shielding for the high energy n and γ (T1).

The top and bottom axial reflectors consist of Inconel and Carbon. Above the top reflector outside the pressure vessel is the same shielding that surrounds the core radially. However, below the bottom reflector there is a porous plug shield consisting of packed cylinders of Tungsten, Beryllium Oxide and Boron Carbide. This plug shield is designed to prevent neutron and gamma streaming, and the

consequent irradiation damage to material in the lower half of the system, which contains the propulsion modules.

In this configuration, the shielding and containment comprise about 2/3 of the total system weight. The shielding could be tailored somewhat for a specific application, thereby permitting possible weight savings. Figure 3.6 is a cross section view of the reactor.

3.6 Turbine - Compressor - Heat Exchangers

The twin T-C-Hx modules are self-contained Brayton machines without the heat source. Figure 3.7 is a sectioned view of the current concept. Helium from the reactor outlet at 1700° F and 1500 psia enters the gas generator turbine through the central pipe of the coaxial piping arrangement. This turbine is directly coupled to the high pressure and low pressure compressors. The Helium exiting the gas turbine generator enters the free power turbine which drives, in this case, the superconducting generator. The hot exit gas from the power turbine enters the recuperator, than the pre-cooler and the L.P. compressor. After the L.P. compressor is an intercooling stage then on to the H.P. compressor which raises the Helium pressure to about 1600 psia, roughly 100 psig over reactor outlet pressure of 1500 psia. After the H.P. compression stage, the Helium passes through the recuperator, then back to the reactor along the outside of the inlet pipe. Once in the reactor, the relatively cool Helium passes up along the outside of the core, cooling the thermal shield. It then enters the core at the top and flows

FIGURE 3.6

Reactor Configuration

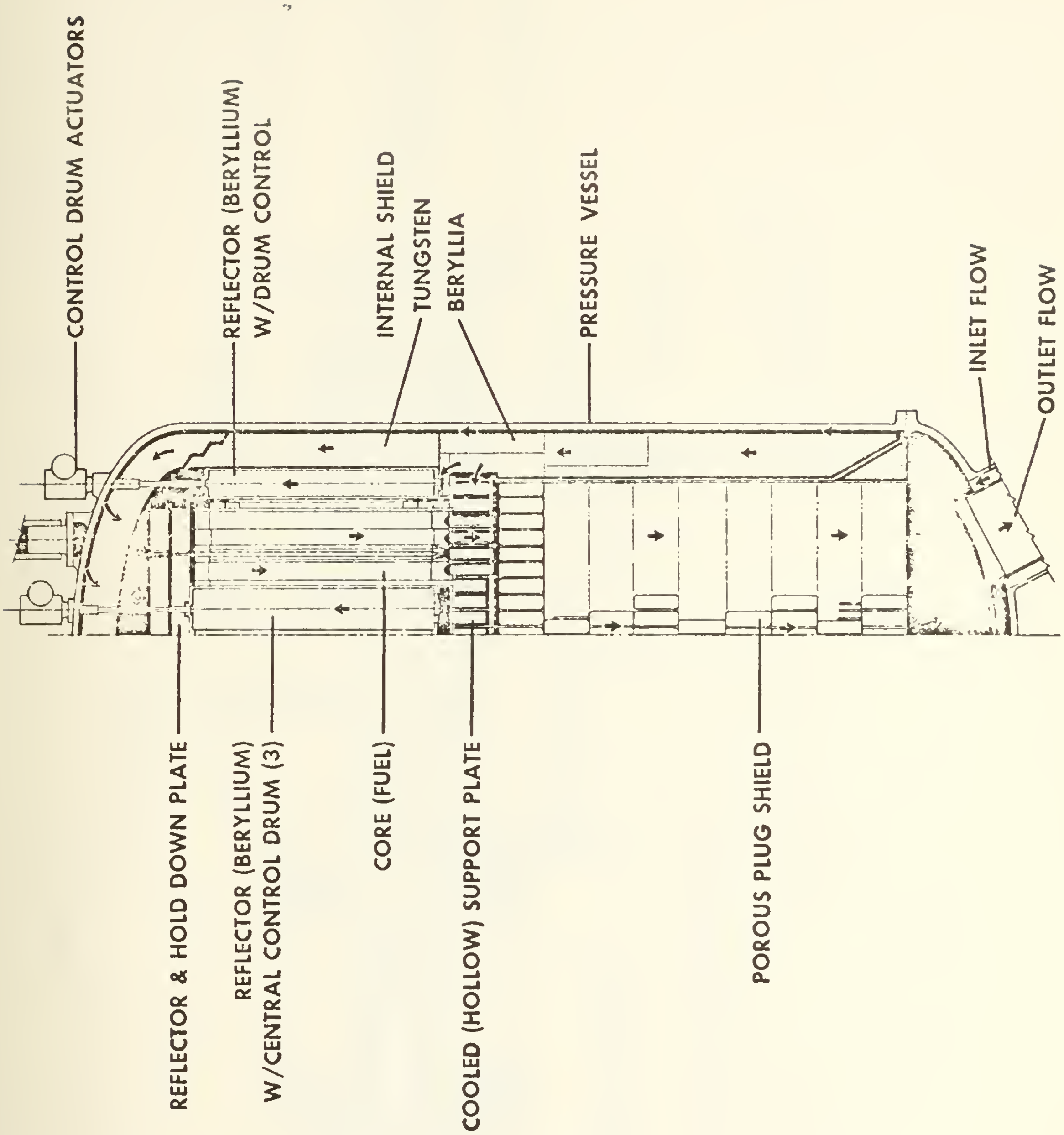
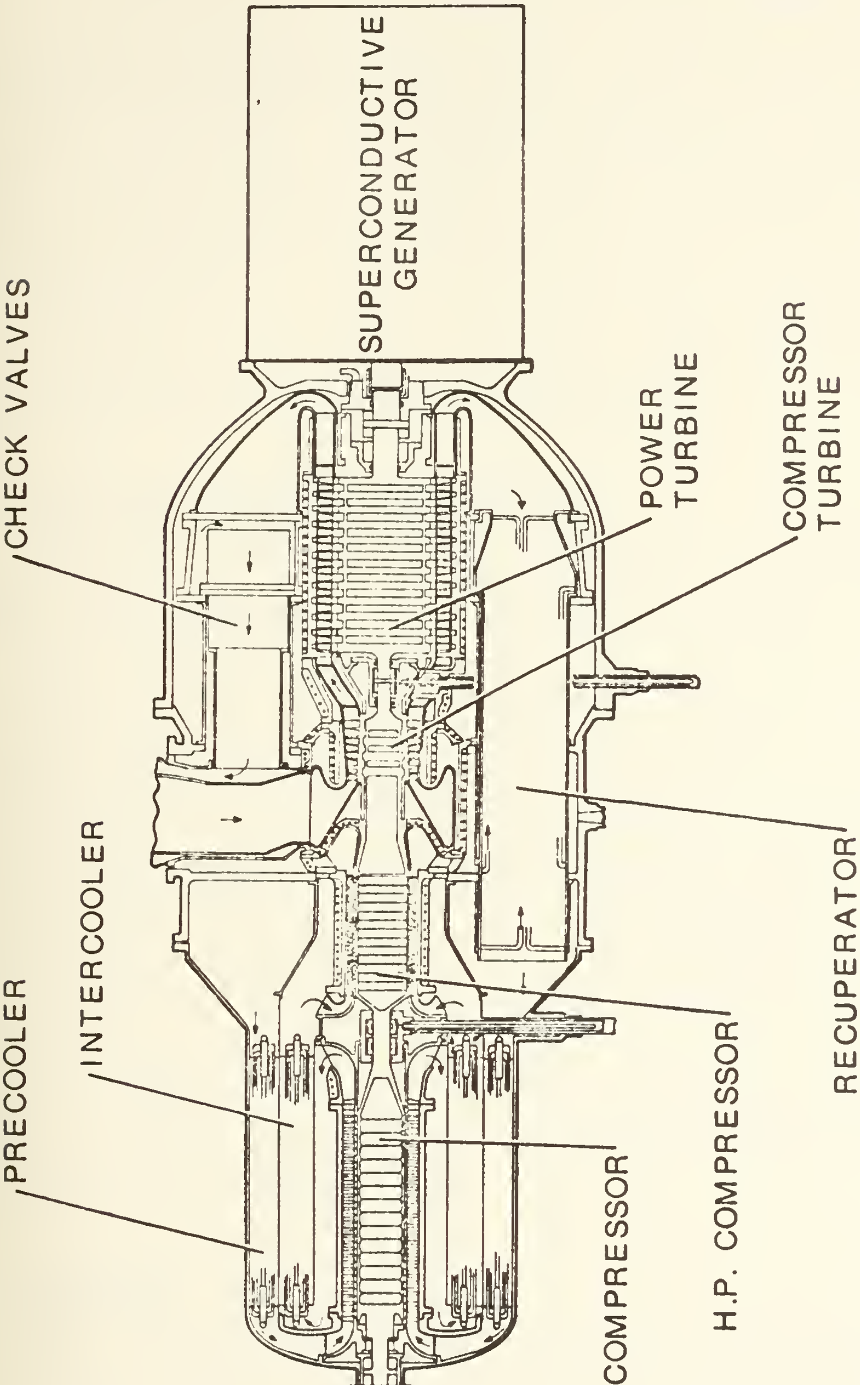


FIGURE 3.7

Turbine-Compressor-Heat Exchanger Module



down through the core and plug shield to the reactor outlet and back into the T-C-Hx. The heat exchangers are all shell and tube counterflow units with the tubes spaced on an equilateral triangular pitch. All tubes are 0.10 inch ID and have a 0.01 inch wall thickness, although the tube spacing varies for the different units. Pure water is used on the tube side of the precooler and intercooler, and a salt water heat exchanger removes the heat from these heat exchangers. The cooling system is shown in Figure 3.8.

3.7 Power Plant Weight and Scaling

TABLE 3-1, gives a weight breakdown of the WANL 140,000 SHP power plant. Two cases are quoted, the first is for a dose rate of 10MR/HR at 20 feet from the reactor centerline, the second for 1MR/HR at the same location. These weights do not include the weights of lift systems and waterjet propulsors, which are estimated to add an additional 1.5 lbs/shp to the totals (C 2). Westinghouse has scaled these results to other power ratings, and as might be expected, higher power levels result in lower specific weights. Figure 3.9, indicates scaling to different power levels for the 10 MR/Hr case.

3.8 Discussion

From a weight standpoint, WANL met their predefined design goal. However, the author feels that there are several areas of technical risk that should be discussed. Westinghouse did not intend this concept as it stands to be a production

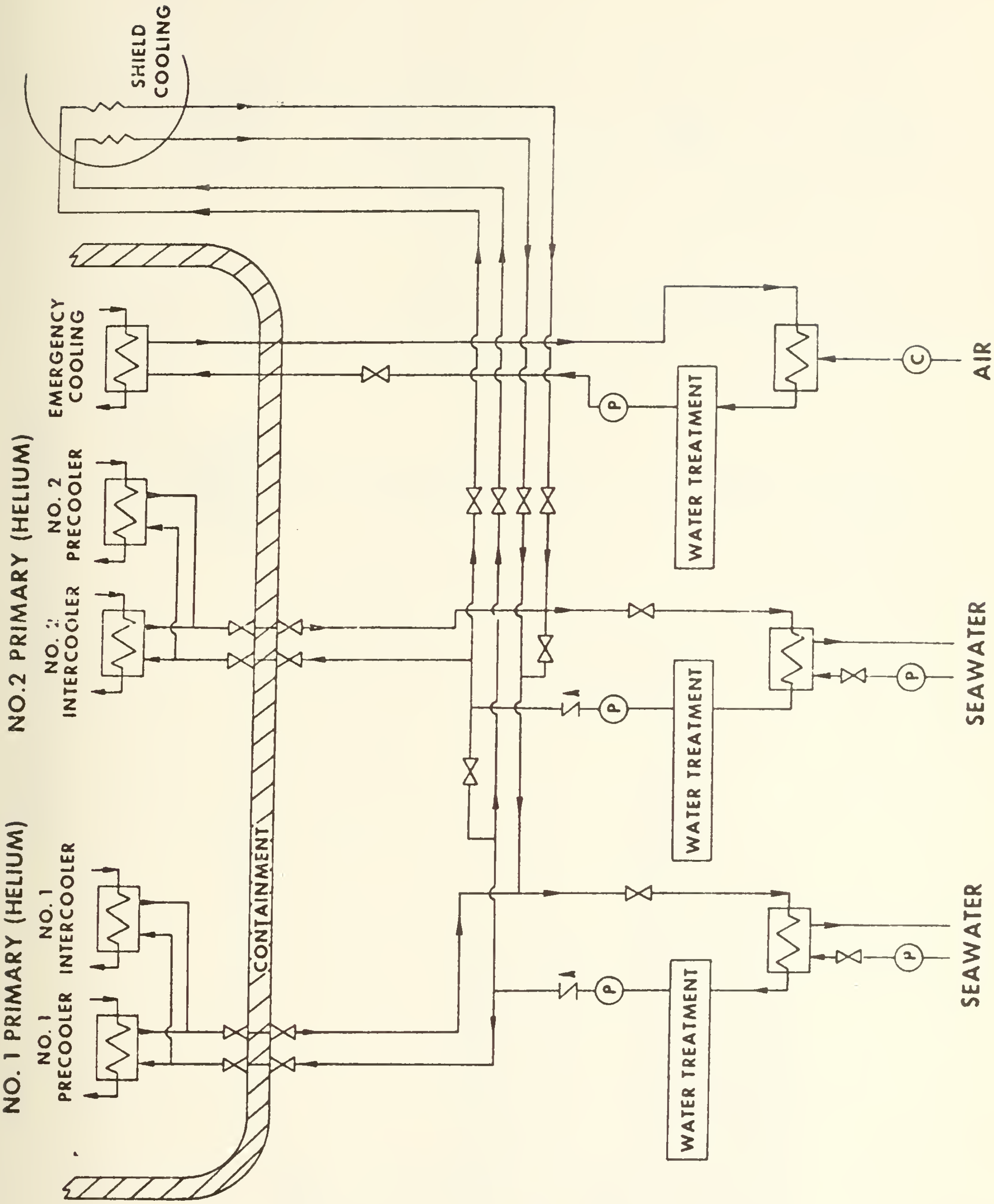


FIGURE 3.8
Secondary Cooling System

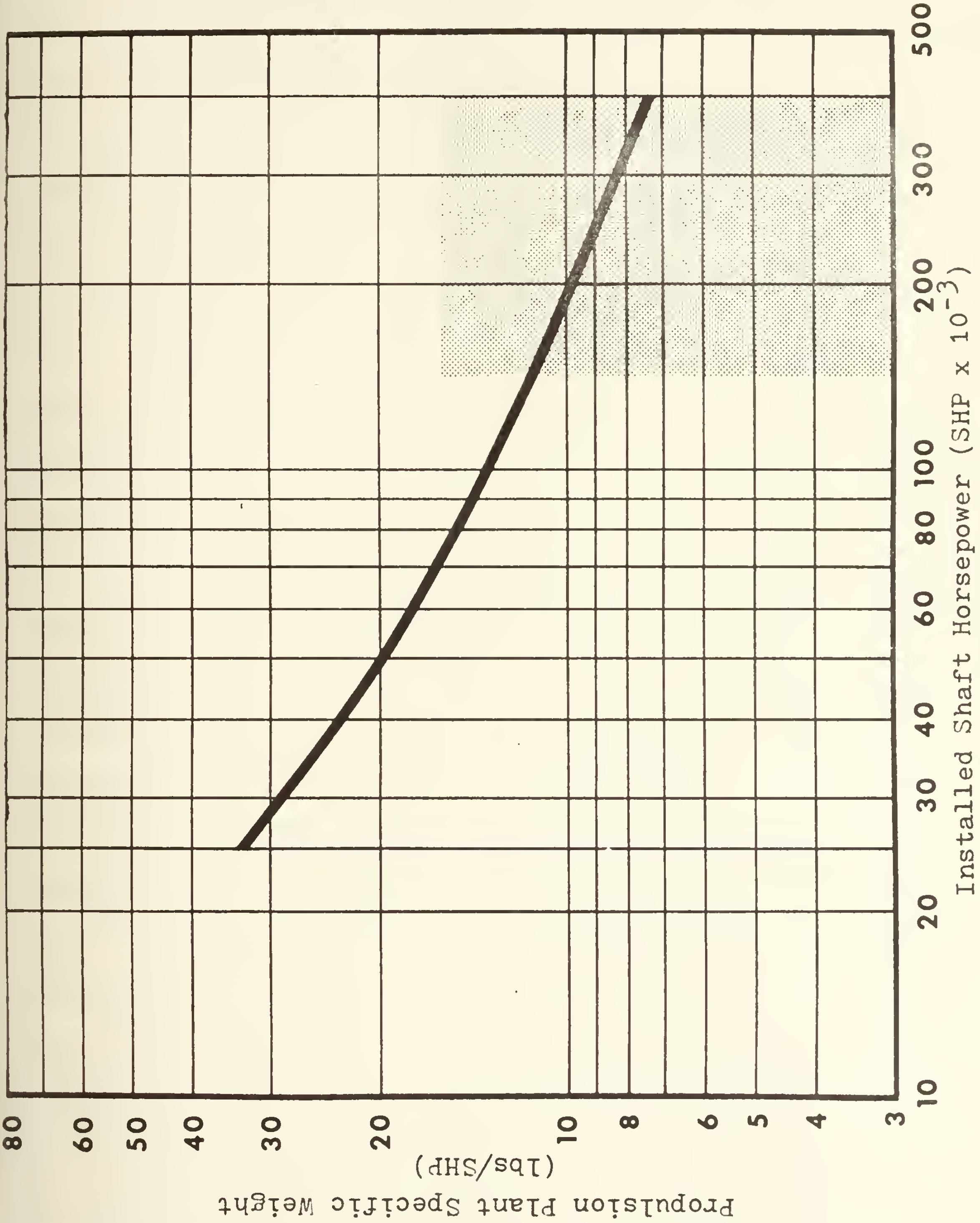
140,000 HP LSWP WEIGHT SUMMARY

	10 MR/HR AT 20 FT		1 MR/HR AT 20 FT	
	WEIGHT (1000 LB)	LB/SHP	WEIGHT (1000 LB)	LB/SHP
REACTOR	18	0.1		
SHIELD	653	4.7	772	5.5
T-C-Hx	122	0.9		
CONTROL GAS STORAGE	37	0.3		
EMERGENCY COOLDOWN	5	---		
HELIUM	1	---		
EQUIPMENT SHIELD & FISSION PRODUCT CLEANUP	466	3.3	632	4.5
WATER & AUXILIARY SYSTEMS	166	1.2		
POWER TRANSMISSION	196	1.4		
	1,664	11.9	(1949)	(13.9)

TABLE 3-1

FIGURE 3.9

Propulsion Plant Specific Weight vs. Horsepower



design. The intent was to identify problems, and propose possible engineering solutions, not necessarily optimal solutions, to those problems. The results indicated to them that the low specific weight power plant was technically feasible. The above notwithstanding, the following areas warrant particular concern from a technical risk viewpoint:

3.8.1 Core flooding

WANL has stated that the reactivity insertion due to core flooding is estimated to be $28.4 (T1). This reactivity insertion would cause the core to become super prompt critical. In a nuclear power plant that is to be used aboard ship, core flooding is a very real possibility. Originally they proposed various solutions, ranging from the insertion of perhaps thousands of B_4C wires into coolant channels, to the use of an easily pyrolizable aminoborane compound. Any one of these could maintain the reactor subcritical. A recent discussion with WANL personnel (T2) indicates that the current preferred concept is to use a spectral shift type poison such as Gadolinium in the reactor core. Gadolinium has a relatively small neutron absorption cross-section in the epithermal region, so would have little affect on neutron economy during normal operation. In the thermal energy range, however, it has the highest known neutron resonance absorption cross-section. During a core flooding accident, the overmoderated neutrons slowing down through the thermal range could be effectively absorbed in the Gadolinium, rendering the core sub-critical. No matter

which method is used core flooding is a serious consideration for these Helium cooled, graphite moderated cores.

3.8.2 Superconducting generators, motors, power transmission systems and auxiliaries.

Although Westinghouse states that the S.C. machinery is not vital to the feasibility of this concept, S.C. machinery looks like the most promising means of transferring large blocks of power to the various users in an SES. With large SES's, and the consequently longer distances between power production and consumption, it appears as if S.C. machinery may be the only feasible solution.

In his keynote address at the 1972 Applied Superconductivity Conference held in Annapolis, Maryland, RAdm. Carl O. Holmquist, USN, Chief of Naval Research, said (H2):

> "For propulsion plants, superconductivity promises a substantial increase in reliability, a drastic reduction in size and weight, and the inherent flexibility of an electric drive. Such a propulsion system would not only have application to ships and submarines but to newer vehicles such as hydrofoil boats and surface effect ships.
>
> Each time this group has met since 1966, the promise of applied superconductivity has grown brighter. This time, we can see the likelihood that within a five-year period the essential characteristics of superconducting electrical ship propulsion devices -- whether they be A.C., D.C. or hybrid -- will have been demonstrated to the point where they may be realistically considered for Fleet use."

There are many institutions both in the U.S. and abroad working on S.C. machines, but the current status indicates that only relatively small power level laboratory machines are in operation. The promise of high power level superconducting

machines for ship propulsion is probably not achievable within the near future. Nevertheless, the possibility of high power level machines in the 1990's can not be ruled out.

This could be an area of considerable risk especially if a long term reactor development program was depending on S.C. machinery development in order to demonstrate total system feasibility.

3.8.3 Fission product retention

Because the primary system flows through all the T-C-Hx components, it can be expected that any nongaseous fission products that escaped into the primary coolant would plate out somewhere in the system. The fission product cleanup system is designed to purify the primary coolant. It is not a full flow filtration system and can not be expected to trap all fission products. This potential plate-out of fission products could pose a serious health hazard to ships crew and maintenance personnel, while unduly complicating the maintenance procedures. Although the expected fission product retention is estimated to be better than 99.99% (T4), this would need to be demonstrated conclusively before a propulsion plant of this type would be considered acceptable.

3.8.4 Reliability/Maintainability/Availability (RMA)

The maintenance philosophy that underlies the WANL design is shore facility repair. Only minor items are repairable by shipboard personnel, and none of the major items in the power train are accessible. The system availability design goal for a six month mission was .95. Although this

was not full power availability, it was for a "fairly heavy duty cycle" (T3). The use of availability here is defined as the probability that the system will be working when called upon in the future. The system was designed with a high availability goal, and despite the uncertainties in failure data of the individual components (Mean Time Between Failure, MTBF, and Mean Time To Repair, MTTR) Westinghouse asserts that the availability goal can be met. The approach was taken that no single credible failure could cause the total system to fail. This coupled with the resulting redundancy and parallel systems resulted in a system which Westinghouse claims exceeds the Availability design goal (T1).

WANL has considerable experience in engineering reliable reactor systems, and engineering judgment was used to extrapolate or estimate component failure data, nevertheless the author questions the resulting high availability. There appear to be too many uncertainties in the development of various key system components such as the high power density, long lifetime core or the superconducting power system. The author's skepticism is not based on a detailed analysis of the system fault trees (none existed), or reliability block diagrams. Rather it is based on personal experience as a shipboard Engineering Officer. Operating equipment in a controlled laboratory environment is much different than operation at sea.

This is not to say that this availability is not attainable. Perhaps a completely enclosed system is less

susceptible to failure. There is one thing certain though, and that is that an at sea failure would be nearly impossible to fix. This inability to repair a power plant at sea should it fail in any way, could prove to be unacceptable from a military viewpoint.

3.8.5 Controllability

This area combined with the absolute necessity of ensuring safe operation of the reactor plant is one of considerable importance for a Naval application. Naval ships are of necessity subject to sometimes rapid changes in propulsive power demand. The control system for the WANL concept is designed to accomodate power changes of 3%/second in the range of 25% to 100% full power. This design value may or may not be acceptable in a particular application. Westinghouse states that it is not an item that would have a major impact on the final system design, should it be necessary to change it.

The area of off-design or emergency situations is equally if not more important. Because of the high temperatures, flow rates and pressures in the system, such accidents as loss of coolant (LOCA) could have serious repercussions. Such occurrences have been considered in the design, but the backup systems must be extremely reliable. Again because of the high power density, and relatively low C/U ratio, the core cannot act as a heat sink for long time periods, such as in HTGR graphite moderated cores. Emergency cooling would need to be started almost immedately (WANL

estimates in less than 10 seconds) if serious core damage is to be avoided in a LOCA. In the NERVA series there was typically less than 1 second in order to initiate emergency cooling in the event that there was a loss of normal coolant/propellant. It is claimed that the NERVA system operation was extremely reliable. The same design philosophy as used in NERVA was applied to the ship propulsion concept. Nevertheless, there is a serious question of long term reliability of this and other control systems operating in the high temperature, high fluence environment. These questions would have to be answered satisfactorily before ever putting this type of reactor on a ship.

3.8.6 Ruggedness

Not only is the shipboard propulsion plant subject to rapid power changes, but it is also continuously subjected to the random structural loadings from the sea. Stationary power plants are designed to be resistant to various accelerations that might be experienced during an earthquake. However, they are not designed to experience continually varying accelerations due to the heave, pitch, roll, etc. motions that a shipboard propulsion plant encounters.

In addition the warship must be able to withstand, to one degree or another, the effects of weapons that could be set off nearby. The Navy has considerable experience in predicting the effect of shock waves on various structures, equipment foundations, piping systems and hangers, etc. (M5). From a design standpoint they also know that it is not a

trivial task to make various equipments shock resistant.

Westinghouse has stated that their concept, with minor modification could withstand roughly 40g accelerations (T 3). There is some uncertainty in the determination of what loadings and accelerations the SES structure will transmit to the power plant. The effects can vary depending on the ship design and installation. Nevertheless the high speed turbomachinery and small diameter heat-exchanger tubes could be susceptible to flow induced vibrations as well as damage from shock and normal shipboard accelerations. Electronic control equipment and sensors are also susceptible to these problems.

Westinghouse does report that some modification would be required if the maximum design accelerations were set at a higher level, i.e. 100g. No estimate of additional weight (foundation modifications, shock mountings, etc.) was made for the 100g case however, since it was felt to be an unreasonable design goal (T 3).

3.8.7 Operability

Presently there is a relatively large cadre of experienced operators for Naval PWR's. The PWR has been in operation for many years, and its operating characteristics are fairly well known. Because of its inherent stability it is usually operated in a "hands off" manual mode. The WANL concept is designed for automatic control. It is not altogether clear that in an off-normal situation there would be sufficient time for an operator to override a

malfunctioning control system, and take appropriate action.

On the other hand the Navy has two new ship classes, the SPRUANCE class destroyers, and the PERRY class guided missile frigates that have aircraft derivative gas turbines (G.E. LM2500) with automatic control systems. These systems are so complex, that the startup and control of the engines cannot be performed manually (D 1). There may be something to be said for having the operators keep their hands off of the control systems, especially with large complex systems. The Navy is slow to change its views however, and it may be a considerable time before complete automatic control of a reactor system is deemed acceptable. In any case it would have to be able to demonstrate the utmost in reliability and controllability before it could compete (from an operability standpoint) with present Naval PWR's.

3.8.8 Cost

The "bottom line" in the decision making process ultimately is "what will it cost?". Before an expensive reactor development program is undertaken such as this, the decision makers need some assurance that the program will be successful. In today's political environment the government can ill afford the luxury of spending millions and possibly billions of dollars on a program that might not be practical. This is not to say that the Westinghouse concept is not feasible, but with any program there is the chance that the end product will not attain the goals initially set for it. There are several development programs that would have to be

undertaken in parallel, including fuel development, materials development for the high temperature helium environment, and superconducting machinery. A failure or delay in any of these programs could cause a failure or delay of the final system design. Westinghouse does not consider any of these areas to be one of high technical risk (T1). In fact because of what they consider to be initial design conservatism they feel confident that the weight goals can be met with a resulting feasible, practical propulsion plant.

The other cost that must be considered is the cost to the country of not developing a low specific weight power plant. This is a very sensitive area and unfortunately involves both politics as well as long range National Defense issues.

Although there is no disagreement as to the ultimate advantages of low specific weight, the cost, development times and development risk involved appear to be controversial.

3.9 Summary

In concluding this chapter, several key points should be reiterated.

- Westinghouse has concluded that a low specific weight propulsion plant for High Performance ship applications is technically feasible.
- Westinghouse concludes that they can design this system with an availability that exceeds the design goal of .95 for a 6 month mission.

- Westinghouse concludes there are no areas that constitute "high" technical risk.

The author feels that the following are areas of "some" technical risk.

- Core flooding.
- Superconducting machinery development.
- Fission product retention.
- Reliability/Maintainability/Availability.
- Controllability.
- Ruggedness.
- Operability.
- Cost.

Chapter 4

MODIFIED POWER PLANT

4.1 Background

Despite claims of high availability for the WANL baseline concept (T3), a less compact, more accessible and maintainable concept might be more desirable. To that end, the baseline concept has been modified here by removing the turbomachinery and heat exchangers from inside the containment. In order to do this, and to confine all potential fission product releases, a two-loop, or indirect cycle was chosen. This design allows a containment of the primary loop only. Furthermore, because of the inaccessibility of the heat exchangers they too were modified. The various heat exchangers were removed from the T-C-Hx modules and redesigned as standard counterflow shell and tube units, with individual shells and end pieces. The remainder of the components were assumed to be identical to the baseline concept, and Westinghouse weights were used for these.

Some of the reasons for a modified cycle include:

1. A margin exists between the baseline concept power plant weight, and the predefined design goal for the baseline SES. If one assumes 2 Westinghouse power plants each rated at 231,000 SHP and include the estimated weights for waterjets and lift fans, the power plant specific weight is about 12.6 lbs/shp

(for the 1 MR/HR case). Considering again Figure 2.2 this would suggest that either the ship could become smaller, or a margin of from 2.2-4.4 lbs/shp exists for the 11,700 ton SES. The goal was then to make the above indicated changes, and try to remain within the 2.2 to 4.4 lbs/shp constraint.

2. By moving the T-C-Hx outside the containment the number of contaminated components from fission product plate out in the primary system is reduced.
3. The heat exchangers and turbomachinery can be demodularized for easy maintenance.
4. The reactor itself is partially "de-coupled" from the immediate effects of transients in demand power.
5. It was felt that this approach would increase system availability. Westinghouse has studied the possibility of an indirect cycle however and concluded that the availability may actually be lower (T1).

4.2 <u>Indirect Brayton Cycle</u>

In order to retain as much resemblance to the original Westinghouse concept, Helium has been chosen as the working fluid in both the primary and secondary systems. Furthermore the core inlet and outlet temperatures and pressures are the same, so that a core redesign is not necessary. The secondary system is identical to the baseline power plant in functional arrangement, including the high pressure turbine driving two

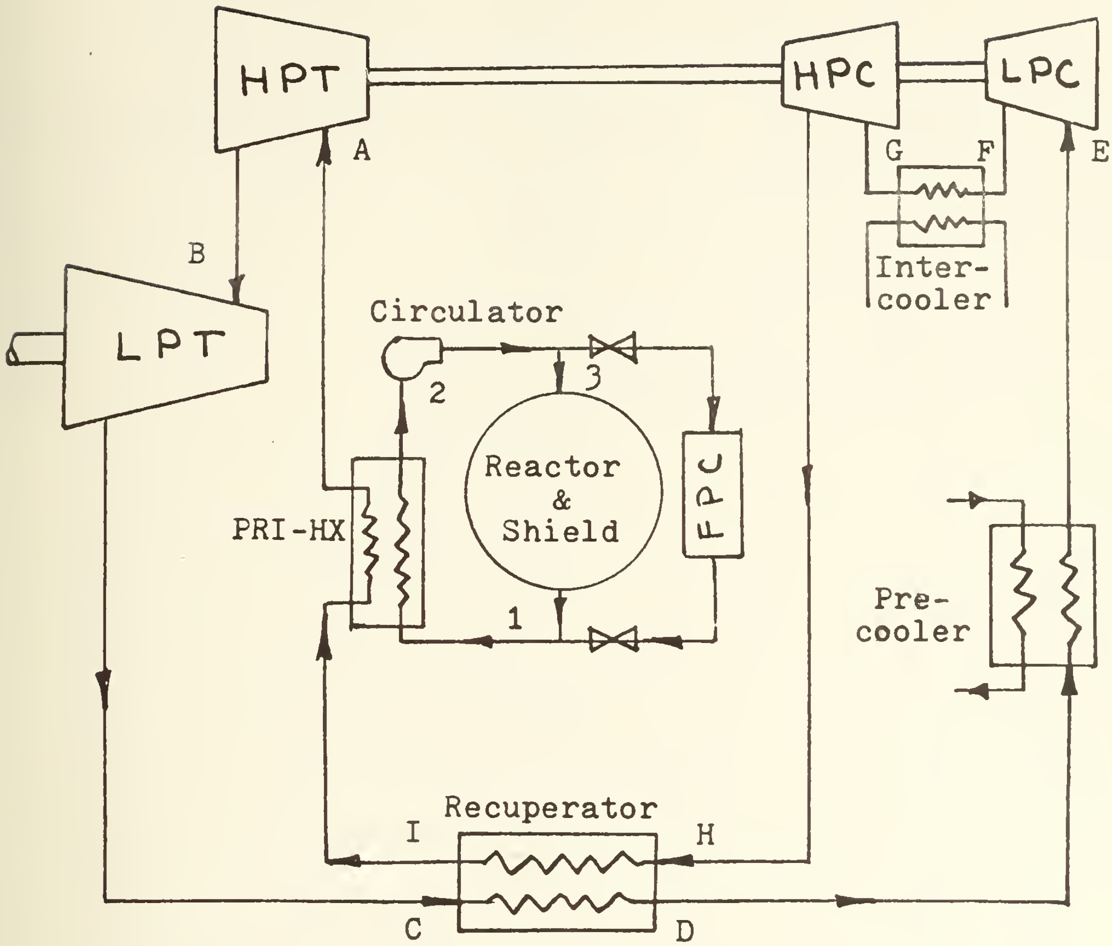
compressors, the free power turbine, recuperator, precooling, and one stage of intercooling. The main difference is that the reactor core in the baseline concept is replaced by a primary heat exchanger (PRI-Hx) in this design. The other item is the addition of circulators to provide the necessary pumping power for the Helium in the primary system. Figure 4.1 is a schematic of the system flow paths.

Since the turbine inlet temperature at A is now lower than the reactor outlet temperature at 1, the efficiency of this new cycle would be lower because of the introduction of the PRI-Hx. The secondary system cycle state points are no longer the same as in the baseline reactor, for two reasons. First, the temperature at A is lower than before and secondly, the relatively high pressure drop through the reactor has been replaced by a much lower pressure drop through the primary heat exchanger. It is also considered desirable to have any system leakage into, rather than out of, the primary system, in order to avoid possible contamination of the secondary system. This required a higher secondary system pressure in the primary heat exchanger, and a pressure of 1600 psia has been chosen for point A. This compared to a primary system pressure of about 1500 psia in the PRI-Hx.

Since there are now several changes to the original cycle, a computer code has been written (Appendix A) to perform the system cycle calculations. This code allows a parametric analysis of the cycle to be conducted. For a

FIGURE 4.1

Indirect Brayton Cycle



State Point	Description
A	HP Turbine inlet (HPT)
B	LP Turbine inlet (LPT)
C	Recuperator inlet - hot side
D	Recuperator outlet - hot side
E	LP Compressor inlet
F	Intercooler inlet
G	HP Compressor inlet
H	Recuperator inlet - cold side
I	PRI-HX inlet (secondary loop side)
1	Reactor outlet (primary loop)
2	PRI-HX outlet (primary loop)
3	Circulator outlet/ Reactor inlet

high pressure turbine inlet pressure (P_A) of 1600 psia and a fixed heat exchanger effectiveness (ϵ_{PRI}), the turbine outlet pressure (P_B) was varied to determine the resulting state points and the cycle efficiency. The resulting values of efficiency were plotted against the High Pressure Turbine (HPT) pressure ratio (P_A/P_B), for various values of ϵ_{PRI}. These curves are shown in Figure 4.2. For the purpose of the above analysis, the following parameters were specified

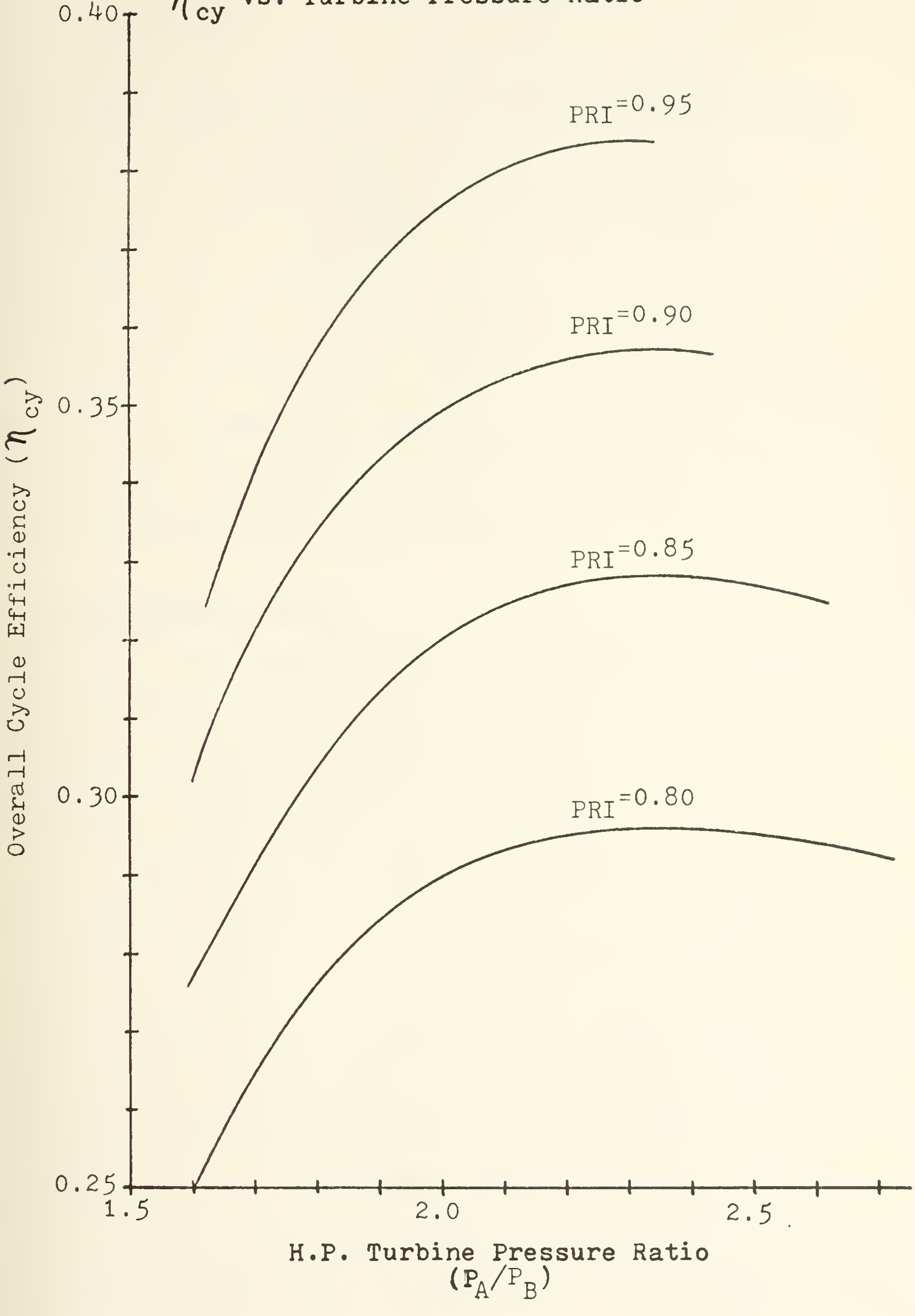
Reactor outlet temperature	T_1 = 1700° F
Reactor outlet pressure	P_1 = 1500psia
Reactor inlet temperature	T_3 = 1264° F
Reactor inlet pressure	P_3 = 1590psia
H.P. turbine inlet pressure	P_A = 1600psia
All heat exchanger pressure drops	Δ_p = 10psia
Precooler/Intercooler Helium outlet temp.	T_E=T_G=560° R
Turbine efficiency	η_T = .90
Compressor/circulator efficiencies	η_C = .85
Helium specific heat(BTU/lbm-°R)	C_P = 1.241
Helium specific heat ratio	γ = 1.66

Given the desired net work output of 231,000 SHP, and the above parameters, the code determines all the state points, the recuperator effectiveness, the required reactor power, the circulator work, primary and secondary flowrates, and the overall cycle efficiency. A sample output is found in Appendix A.

The reason for determining the effect of ϵ_{PRI} on efficiency was that in sizing the primary heat exchanger, the

FIGURE 4.2

η_{cy} vs. Turbine Pressure Ratio



effectiveness would have a significant impact on its dimensions and weight. At least one candidate cycle was chosen from each of the four effectiveness curves of Figure 4.2 and used as inputs to the heat exchanger design. This was done during the early investigation because of the uncertainties in the final power plant characteristics. Although high cycle efficiencies were desirable, they had to be balanced against the required weight of the high effectiveness heat exchangers. Even though a high cycle efficiency would result in a smaller core size, the problems involved with the resulting longer length primary heat exchanger might make the cycle infeasible.

4.3 Heat Exchanger Design

Once the cycle state points were determined, including system flow rates, the heat exchangers were sized. As mentioned previously the approach taken was to design each heat exchanger (Hx) as an individual unit.

In the design of heat transfer equipment there are several parameters that the designer is free to specify. From the standpoint of this work, the temperatures, flow rates and approximate pressure levels were inputs. Approximate pressure levels is used here to indicate that although a pressure drop was specified in the cycle calculation, e.g. between the L.P. compressor outlet and H.P. compressor inlet, this included more than the pressure drop across the heat transfer matrix core. In particular, the pressure drops

between cycle state points include frictional losses in the inlet and outlet pipes, expansion and contraction losses, as well as pipe bends. Because these pressure drops were approximate values and had little effect on the resulting cycle, it was felt justified in using them in the cycle calculations. On the other hand the pressure drop in the heat transfer matrix itself has a significant impact on the design of that component.

Other parameters that are fixed by the designer are tube diameter, wall thickness, tube spacing and arrangement. Another parameter is the determination of which fluid is to be on the shell side, and which is to be on the tube side.

A general computer code was written to size all of the heat exchangers, including the primary heat exchanger, recuperator, precoolers, intercoolers and also the sea water/fresh water Hx. A description of this code is found in Appendix B. The accuracy of this code (HXSIZE) was verified by attempting to duplicate the Hx sizes used in the Westinghouse concept, given their temperatures, flow rates, tube sizes and pressure drops. The results were almost identical to the baseline concept Hx's.

The same heat exchanger core pressure drops that Westinghouse used, were also used in this study in order to retain some similarity with the baseline. Although larger tube sizes were used here, the tube spacing to outside diameter ratio (P/D) was kept the same. The baseline concept had 0.12 inch OD tubes in all of the heat exchangers except

the sea water Hx (0.25 in OD). This study used 0.25 inch OD tubes in all Hx's except the sea water Hx where 3/8 inch OD tubes were used.

Some of the important outputs of HXSIZE included the length, number of tubes, velocities etc. for the two streams, the shell diameter, shell thickness and weight, tube sheet thickness and weight, end closure thickness and weight, total heat exchanger weight wet and dry as well as the external piping requirements for both shell and tube side fluids. This information was necessary in order to be able to determine the total weight and volume impact of the heat exchangers. A sample heat exchanger design output is found in Appendix B.

4.4 Reactor Core and Shield Design

The approach taken in determining the dimensions and weights of the core and primary shield was to change as little as possible from the Westinghouse design. A computer code was written to determine dimensions and weights (Appendix C) based on the following:

1. The core had the same power density (262 kw/l) as the baseline.
2. The annular concept was retained, the volume was scaled up using the core L/D of the 140,000 SHP baseline concept.
3. It was assumed that, to a first approximation, the neutron and gamma fluxes at the core surface were the same as for the baseline. Therefore the same shield

arrangement and same material thicknesses were used (R1). For this design however the primary shield surrounded the entire core.

4. The length of the plug shield was reduced.
5. The Helium flow paths were unchanged.

The method of "scaling up" the core and shield was arrived at after considering the alternative, which would require a complete core redesign. The approach described above was considered adequate for this study after discussions with Westinghouse and M.I.T. personnel (T1 , T2 , P3 , R1). Core dimensions and shield material thicknesses and densities for the baseline concept were provided by Westinghouse (T1 , T2 , P3).

The input to the code was the desired power level in Megawatts, and the dose rate at 20 ft from the reactor centerline, either 10 MR/hr or 1 MR/hr. A sample output is found in Appendix C. It contains radial dimensions, lengths and weights of the core, shield materials, pressure vessel and shield container.

4.5 Containment

The containment is designed to surround the reactor core and primary shield, primary heat exchanger, circulators, and the Fission Product Cleanup (FPC) - inventory control system. Some of its functions include:

1. Act as a secondary radiation shield.
2. Contain possible primary system accidents. These

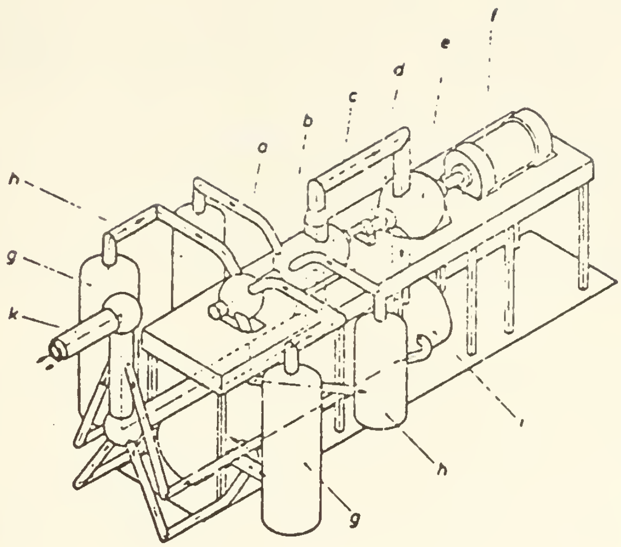
could include pipe rupture, fission product releases etc..

3. Act as a pressure hull against outside sea pressure should the vessel sink.
4. Act as an additional shield against possible missile hazards or collisions.

All of the above were considered in determining the size and thickness of the containment. The final design criteria that became overriding was item 3 above. The design depth that was chosen is 1000 ft, corresponding to an external pressure of about 460 psia. The containment itself was composed of a cylindrical shell with elliptical top and bottom caps. A design factor of safety of 1.5 was used in determining the wall thickness, and the material used had an assumed yield strength of 50,000 psi.

4.6 T-C-Hx Arrangement

For ease of maintenance, a machinery arrangement similar to that of the German Closed Cycle Gas Turbine (CCGT) plant Oberhausen II (B1) was used. Figure 4.3 is a profile view of the machinery arrangement. The number of Hx units was chosen to be the same as for Oberhausen, again due to the uncluttered arrangement. The baseline concept of two power producing loops was retained. As a result, associated with each reactor, are two of the T-C-Hx complexes as indicated in Figure 4.3.



a. LP Compressor

b. HP Compressor

c. HP Turbine

d. Gear

e. LP Turbine

f. Generator

g. Precooler (2)

h. Intercooler (2)

i. Recuperator

k. Concentric Double Duct

FIGURE 4.3
OBERHAUSEN II Isometric

4.7 Conclusions

As a result of the decision to adopt an indirect cycle plant, with Helium as the working fluid, there were several design decisions that had to be made. The final goal was to determine if a modified power plant is feasible. This is done primarily from a weight standpoint, while a qualitative estimate of the effects of other parameters is made.

The results of the design process, a physical description of the power plant, is in Chapter 5. Chapter 5 also describes some of the design decisions that were made and the reasoning behind them.

Chapter 5

PROPULSION PLANT CHARACTERISTICS

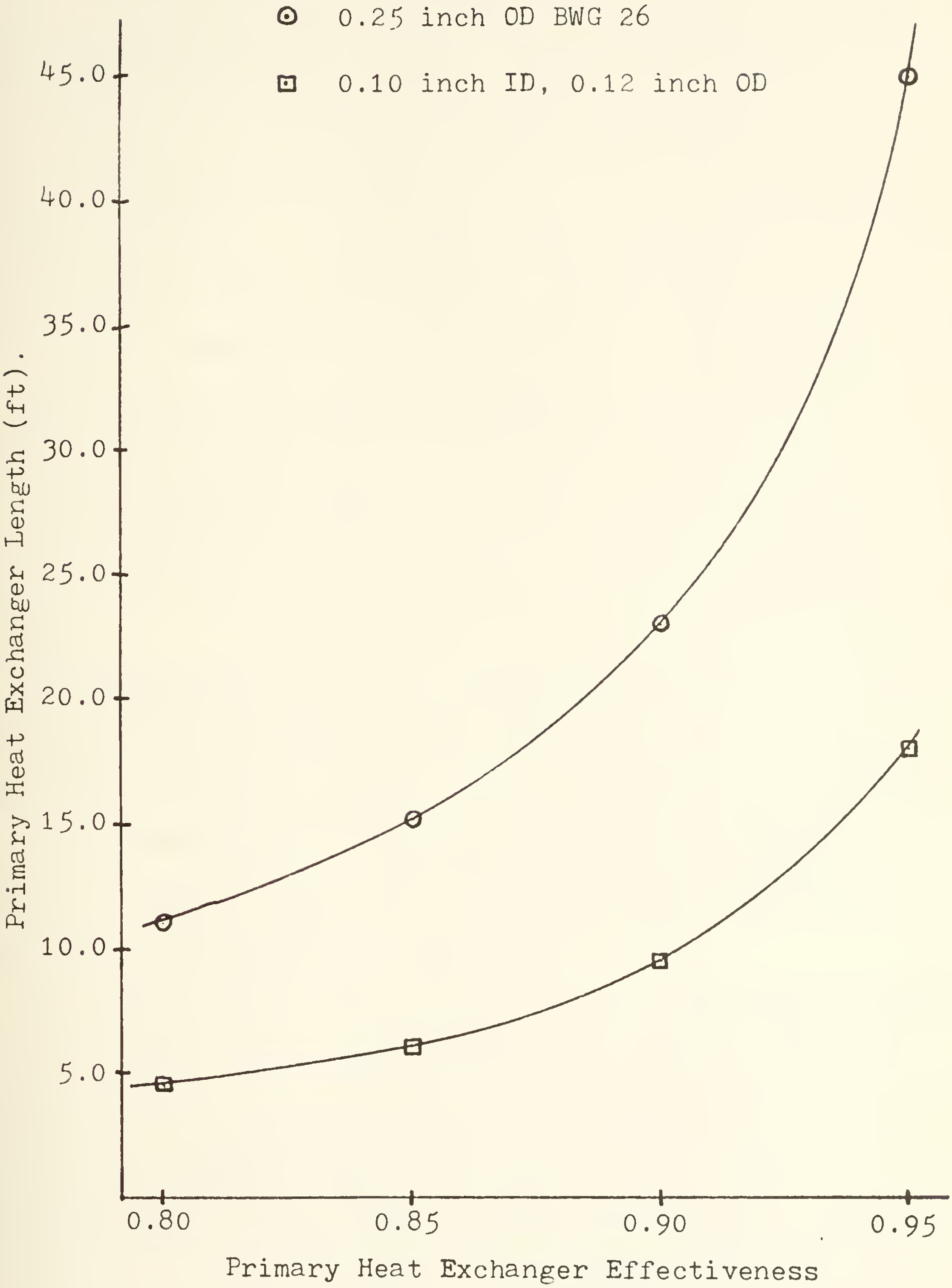
The methodology, or approach taken to design the modified propulsion plant (Indirect Brayton Cycle) was discussed in Chapter 4. This chapter will describe the principal characteristics of the final propulsion system. This chapter will also compare the modified power plant with the Westinghouse baseline, in terms of overall efficiency, size and weight.

5.1 Primary Heat Exchanger

Figure 5.1 is a plot of primary heat exchanger core length versus heat exchanger effectiveness, as determined by the computer code HXSIZE. The upper curve represents the tube size selected for the modified propulsion plant. The lower curve represents lengths that would be obtained if the smaller tubing of the Westinghouse recuperator was used. For the 85% effectiveness case the inside shell diameters for each Hx are about 4 feet. The length is a complex function of pressure drop, tube spacing, temperature drop, flow rates, and fluid properties that is solved for explicitly in HXSIZE. However, for the temperatures, pressures and flow rates determined in the indirect cycle computer code for each effectiveness, the results from HXSIZE plotted in Figure 5.1 are well represented by

$$L = L_{REF}\left(\frac{D_o}{D_{oREF}}\right)^{1.23} \quad . \qquad (5.1)$$

FIGURE 5.1
PRI-HX Length vs. Effectiveness



At any heat exchanger effectiveness, L_{REF} is defined as the heat exchanger core length for the 0.12 inch OD tube size, and Do_{REF} is 0.12 inches. For example, at an effectiveness of 85%, L_{REF} is 6.12 feet. Using equation (5.1) with a D_o of 0.25 inches the corresponding length is 15.1 feet. The value of L calculated by HXSIZE is 15.16 ft. Although not indicated in Figure 5.1 the relationship of equation (5.1) predicts lengths within approximately 5% for larger tube sizes. If 0.25 inch OD tubes were thought to be too small, one could estimate the effect on length of using ½ inch OD tubes by the use of equation (5.1). For the case just cited, at an effectiveness of 85% the length would be about 35 feet, while for a 95% effectiveness case, the length would be about 106 feet!

Although parametric weight estimating relationships such as this could have been developed, they were not. Instead HXSIZE was used, since it gave considerably more information about the particulars of a given heat exchanger design. Needless to say the total heat exchanger weight followed a trend similar to that found for length.

The indirect cycle has the primary heat exchangers inside the containment. The baseline SES had an overall beam, in the area of the propulsion plant, of about 120 feet, and a machinery box maximum height of about 40 feet. The arrangement plan has two power plants athwartships, one to port, the other to starboard, with approximately 10 feet on the centerline of the ship reserved for a passageway. In

addition a minimum of 10 feet outboard of each reactor compartment was reserved for ballistic/collision protection systems. This leaves a maximum of 45 feet athwartships for each reactor compartment. Since it was decided to have a vertical cylindrical containment with elliptical top and bottom portions, this limited the cylinder diameter to something less than 45 feet, with an overall height limited to being less than 40 feet.

The primary heat exchanger was one of the most important considerations in determining the size and weight of the propulsion plant. As a compromise between length, weight, containment size, and overall cycle efficiency, a primary heat exchanger effectiveness (ϵ_{PRI}) of 85% was chosen. The resulting propulsion plant had an overall efficiency (η_{cy}) of 32.8%. Furthermore, for reliability/redundancy considerations it was decided to choose a system with 4 primary heat exchangers. Each pair of two would interface with one of the two T-C-Hx units. Since the total power plant was designed to 110% full power, each of the PRI-Hx was designed for a maximum flow rate of 25% of the total full power Helium flow rate plus 10% margin.

The materials used for the primary heat exchanger must be capable of withstanding high operating temperatures (max. 1700° F) and high operating pressures (max. 1610 psia), as well as thermal cycling and pressure cycling, from normal operation and startup/shutdown. In addition, it would have to meet shock and vibration standards as discussed in

Chapter 3. Some candidate materials include Inconel alloy 625, Haynes alloy 188 etc. (W2 , C4). For purposes of the heat exchanger design, a pseudo-material with a density of 534 lbs/ft^3 and a yield strength of 60,000 psia was chosen. This was felt to be representative of high strength, high temperature alloys, although Haynes alloy 188 has a somewhat lower yield strength. The other reason that a specific material was not selected was the uncertainties involved with its use in an high temperature Helium environment. Considerable work is being done on the high temperature properties of materials in Helium atmospheres. Impurities in the Helium can cause a "corrosion creep" phenomenon in metals, in some respects analogous to corrosion fatigue. Test results in High Temperature Reactor (HTR) helium suggest that Titanium and to a lesser extent Aluminum stimulate corrosion creep when added to alloys, whereas Tungsten and Niobium act as inhibitors (H3). In view of the above it was felt that rather than selecting a material that might prove to be inappropriate, general strength properties would be specified.

5.2 Cycle State Points

The state points corresponding to a cycle efficiency of 32.8% are shown in Table 5-1. Figure 5.2 is a schematic of the cycle, indicating these state points. The primary system flow rate is equal to the secondary system flow rate and is 448. lb_m/sec. Figure 4.2 indicates that 32.8% cycle efficiency is near the maximum value available with a primary

FIGURE 5.2

Indirect Brayton Cycle

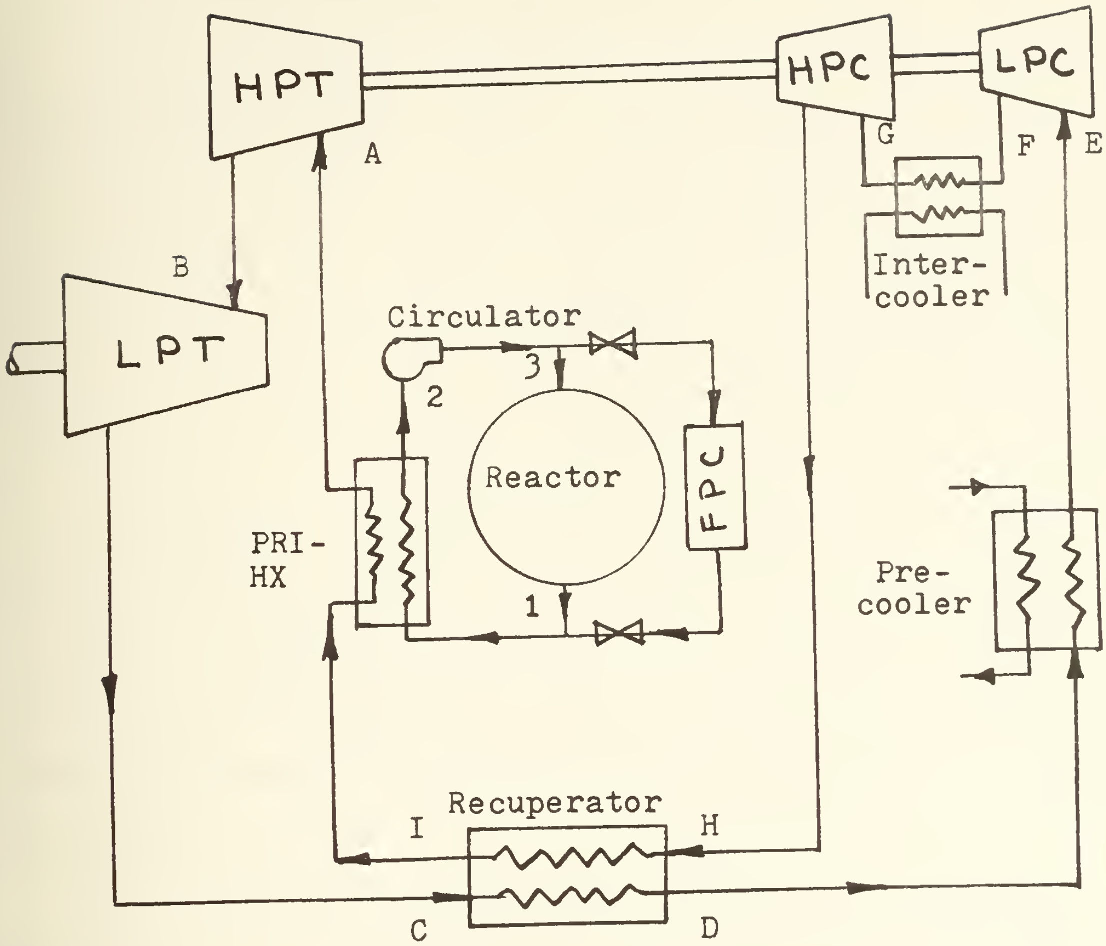


TABLE 5-1

Point	Description	T(^{o}R)	P (PSIA)
1	Reactor outlet	2160.	1500.
2	PRI-HX outlet	1226.3	1490.
3	Reactor inlet	1264.	1590.
A	HP Turbine inlet	1995.2	1600.
B	LP Turbine inlet	1454.7	650.
C	Recuperator inlet	1122.9	311.6
D	Precooler inlet	891.7	301.6
E	LP Compressor inlet	560.	291.6
F	Intercooler inlet	830.3	692.4
G	HP Compressor inlet	560.	682.4
H	Recuperator inlet	830.3	1620.
I	PRI-HX inlet	1061.5	1610.

heat exchanger effectiveness of 85%, at the specified conditions. The net cycle work of 231,000 SHP for one plant, or 172 MW, requires 29,700 HP for the circulator work in the primary system at full power. It is proposed to accomplish this with 4 circulators each rated at 7500 HP. Each primary heat exchanger is to have a circulator associated with it. The circulator motors are intended to be mounted external to the containment, while the circulator itself is in the primary Helium flow stream, just at the outlet of the primary heat exchangers. The motors are to be superconducting electric motors, and have an alternate power source, for startup, or emergency situations. The required reactor power to provide for one, of the two plant 231,000 SHP full power requirement, is 525 MW. The total ship installed power is therefore 1050 MW.

The system flow diagram for the reference baseline design is shown in Figure 3.3. Table 5-2 lists the state points corresponding to this flow diagram. The overall cycle efficiency of the reference was 35.7%. In the Westinghouse design, not all flow rates were equal, but allowance was made for a maximum of 6% bleed flow within components. Also the presence of the Fission Product Cleanup system / Inventory Control system causes some flow rates to be higher than others. The above was not considered necessary for the modified power plant, and hence all flow rates are equal.

TABLE 5-2

Westinghouse Reference Cycle

Component	Temp (^{o}R)	Pressure (PSIA)
Reactor - outlet	2160	1500
HP Turbine - inlet	2131	1488
HP Turbine - outlet	1737	837
Power Turbine - inlet	1737	837
Power Turbine - outlet	1419	474
Recuperator - inlet	1393	468
Recuperator - outlet	896	459
Precooler - inlet	896	458
Precooler - outlet	562	450
LP Compressor - inlet	562	448
LP Compressor - outlet	766	878
Intercooler - inlet	766	878
Intercooler - outlet	559	875
HP Compressor - inlet	559	875
HP Compressor - outlet	741	1611
Recuperator - inlet	741	1604
Recuperator - outlet	1270	1599
Reactor - inlet	1264	1583

Overall Cycle Efficiency, $\eta_{cy} = 0.357$

(Reference T1)

5.3 Heat Exchangers

Once the cycle state points and flow rates were determined, the recuperator, precooler and intercooler were sized. The recuperator has the same $\frac{1}{4}$" BWG 26 tubes as used in the primary heat exchangers, with the same pitch to diameter ratio of 1.35. The coolers have the same tubes, but with a pitch to diameter ratio of 1.2333. These P/D ratios are the same as those used in the respective units by Westinghouse, although the tube sizes are larger. All heat exchangers are designed with the same material parameters as the primary heat exchangers, although different materials might properly be utilized in the lower temperature recuperator, or the coolers. All heat exchanger shells are designed to withstand the maximum component pressure in the event of internal leakage, or tube rupture. Shell thickness and weights are determined using a factor of safety of 1.5 above the resulting static design pressure. This may lead to a conservative design. It was, however, the only practical way of getting preliminary weight estimates for the large number of different heat exchangers that were run on HXSIZE. In a detailed design, one would make use of the ASME codes, and take into account such things as general membrane stresses, local membrane stresses, bending stresses, secondary stresses including structural discontinuities at end closure / shell junction, differential thermal expansion, etc.. This is not intended to be a detailed design, therefore the approach described above is considered adequate.

Fresh water from the intercoolers and precoolers rejects heat to a salt water cooler. The salt water cooler has 3/8" BWG 18 (0.049 inch wall thickness) tubes and a pitch/diameter ratio of 1.35, also on an equilateral triangular spacing. It is designed to the same standard indicated above. The material for the salt water heat exchanger is Monel.

Table 5-3 lists important parameters of all of the heat exchange equipments. More detailed information is found in Appendix B and consists of the output of HXSIZE for each heat exchanger. Notice that because a reasonable primary heat exchanger effectiveness was chosen, it does not dominate the weight total as one might expect. In fact, the primary heat exchangers weigh less than the recuperators. Although the overall heat transfer coefficient is slightly higher for the PRI-Hx, the ΔT_{LM} is much higher. The resultant heat flux (q/A) for the primary heat exchanger is over 3.5 times higher than for the recuperator. Now since the thermal duty of the recuperator is only 135.5 MW as compared to 547.1 MW for the primary heat exchanger, the heat transfer areas are almost the same (see Appendix B calculations). One significant contribution to the added weight of the recuperators is the relatively thick tube sheets that are required because of the 1300 psia difference in shell and tube side fluid pressures.

Another important consideration in sizing heat exchangers is the fluid velocities on both the shell and tube side. For the salt water cooler this velocity determined what the tube side pressure drop had to be, given the assumed P/D

PARAMETER / HEAT EXCHANGER (Effectiveness)	FLUID IN SHELL	FLUID IN TUBES	OVERALL LENGTH (FT)	SHELL DIAMETER (FT)	TUBE OD. (INCHES)	NUMBER OF UNITS	# TUBES PER UNIT	PRESSURE IN SHELL (PSIA)	PRESSURE IN TUBES (PSIA)	HX WEIGHT (TONS)	FLUID WEIGHT (TONS)	TOTAL WEIGHT (TONS)
Primary HX ($\epsilon_{PRI} = 0.85$)	He	He	19.7	4.0	0.25	4	18031	1610	1500	40.2	0.2	40.4
Recuperator ($\epsilon_{REC} = 0.79$)	He	He	19.5	6.6	0.25	2	49461	312	1620	63.7	0.2	63.9
Precooler ($\epsilon_{PRE} = 0.985$)	He	H_2O	11.7	3.5	0.25	4	16807	302	70	17.0	8.7	25.7
Intercooler ($\epsilon_{INT} = 0.982$)	He	H_2O	12.4	3.4	0.25	4	15576	692	70	18.3	8.2	26.5
Sea Water HX ($\epsilon_{SW} = 0.841$)	H_2O	Sea Water	38.0	6.4	0.338	2	21183	70	70	120.8	60.4	181.2
								TOTALS		260.0	77.7	337.7

TABLE 5-3

Heat Exchanger Parameters

ratio, and tube sizes. A velocity of approximately 10 ft/sec. is desirable on the salt water side. This is to ensure that the cooler will not become plugged by marine growth at lower velocities, nor suffer excessive erosion as a result of higher velocities (F 2).

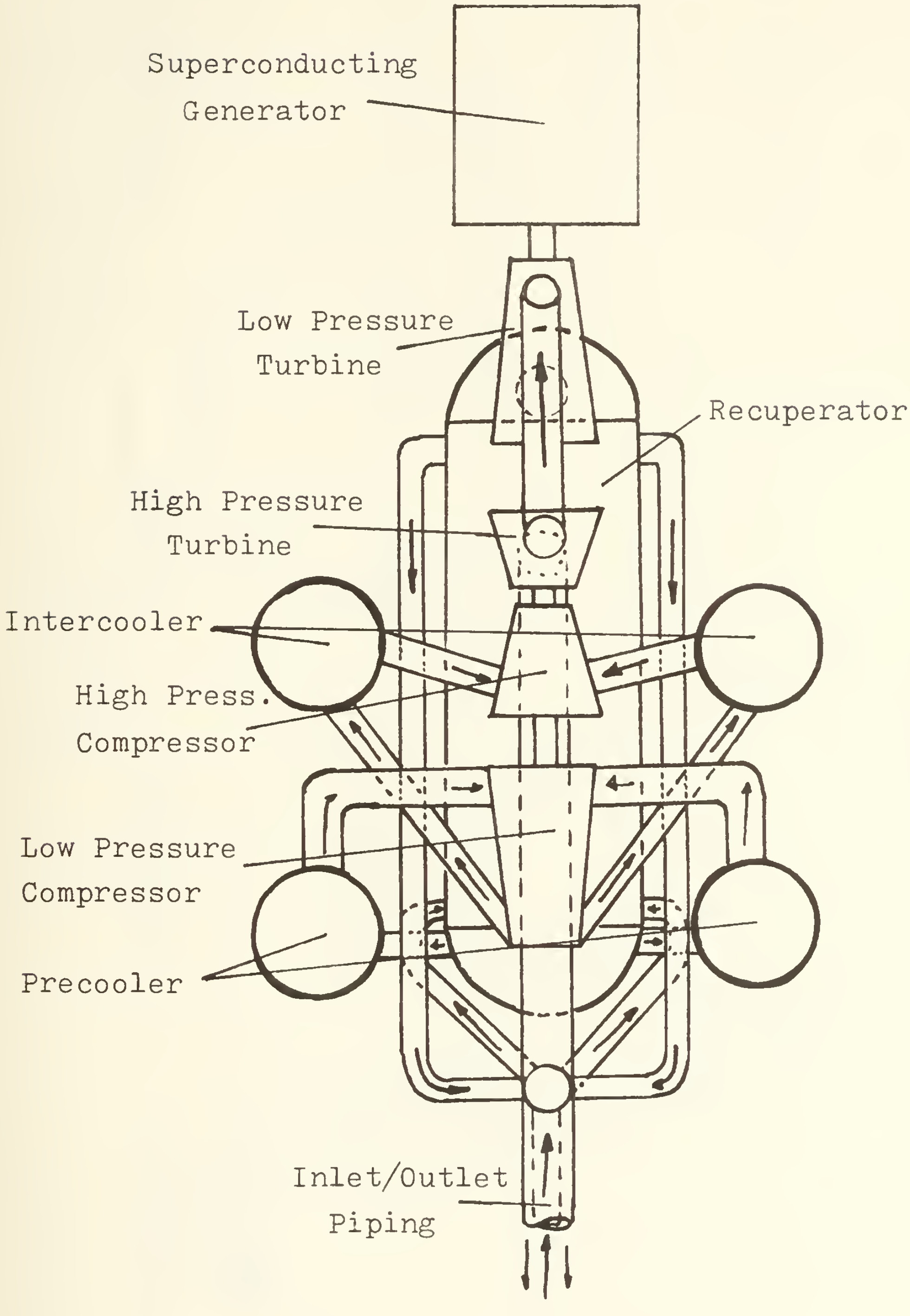
While this was done for the salt water cooler, the only real consideration for the other heat exchangers was to ensure turbulent flow for good heat transfer. For gas flow, the velocities should be limited to between about 10 and 100 feet/sec. (F2). Higher velocities can cause flow induced vibrations that can lead to premature failure of the heat exchanger.

Several of the gas heat exchangers have gas velocities over 100 fps (recuperator and precooler) and in a detailed design, this effect would be an important consideration. Hence, a redesign of these components would probably be necessary. Due to the nature of this study the weights determined were thought to be little influenced by this effect, therefore it was ignored.

Figure 5.3 is a sketch of the T-C-Hx machinery. As mentioned in Chapter 4 the arrangement is identical to that of the Closed Cycle Gas Turbine plant Oberhausen II (B1). The salt water/fresh water heat exchanger is not indicated in the sketch, but is located below the T-C-Hx components, as low as practical in the SES.

FIGURE 5.3a

Top View of T-C-Hx Machinery



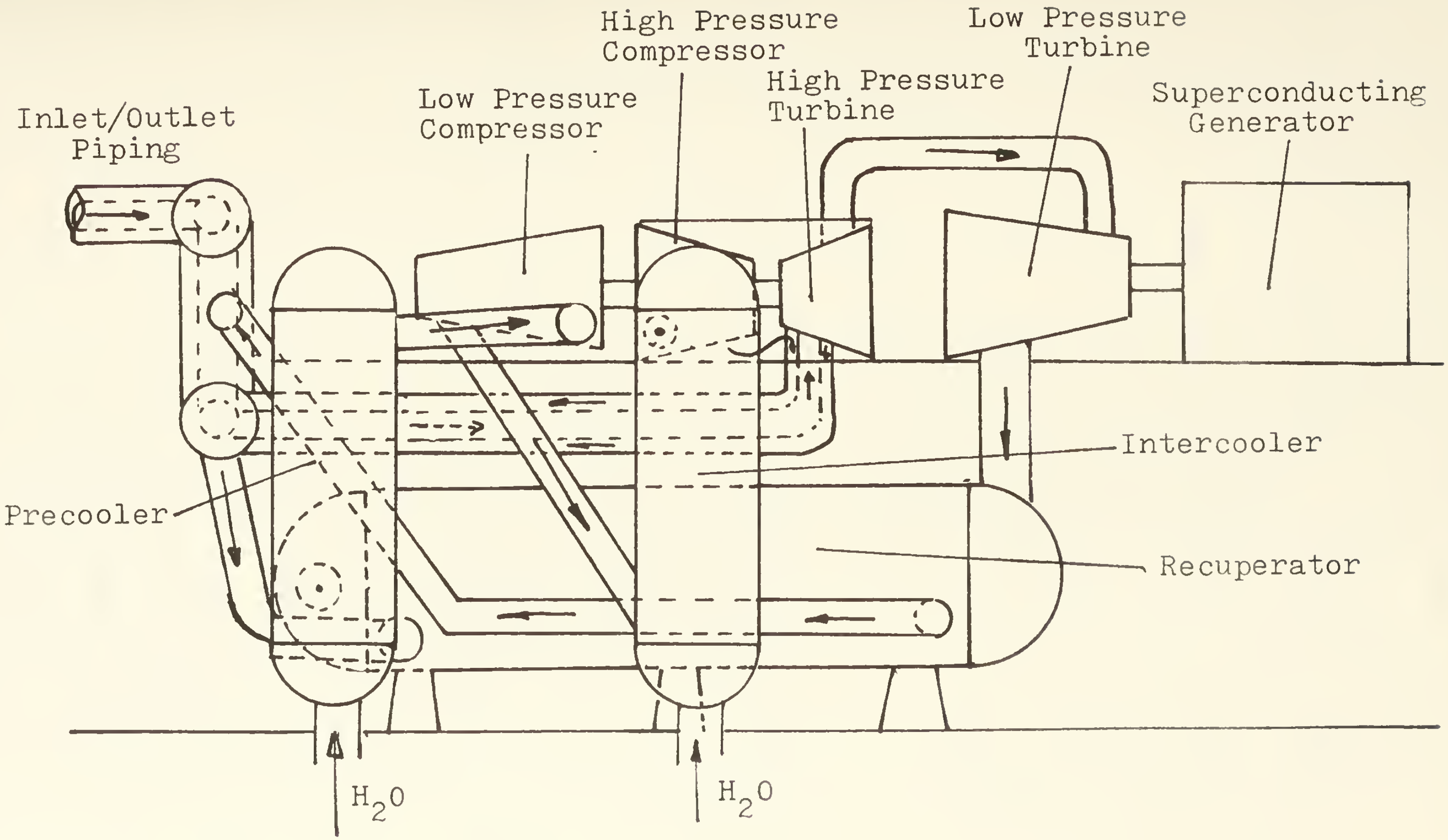


FIGURE 5.3b

Profile View of T-C-Hx Machinery

5.4 Primary Shield and Containment

As mentioned in Chapter 4, the primary shielding thicknesses used were the same as those used in the Westinghouse study. There was one exception however, in that Lithium Hydride (LiH) was substituted for Water. Although it is certainly a more expensive material, it is less dense than water, and at this density does a "better job" of slowing down Neutrons (P 3). If one describes the number density of the neutron "beam" at a point as N_o, then the number density N at some other point x in the medium, in the direction that the beam is traveling is

$$N = N_o \, e^{-\Sigma x} , \tag{5.2}$$

where Σ can be described as an attenuation coefficient (H 1 , M 3). For LiH, Σ_{LiH} is 0.338/in. and for water, Σ_{H2O} is 0.290/in. For the same effective decrease in number density, a slab of LiH need only be 86% of the thickness of the water.

As described in Chapter 4, the computer code SHIELD sized the core, and shield element thicknesses as well as determining the individual and total system weights. The shield dimension and weights were calculated for both the 10 MR/HR and 1 MR/HR case. A cross sectional view of a portion of the shield configuration from the core centerline outward is shown in Figure 5.4, for the 1 MR/HR case. Tables 5-4 and 5-5 list the primary shield dimensions and weights for the 1 MR/HR and 10 MR/HR cases.

The containment was sized by considering the overall primary shield dimensions, the dimensions of the primary heat

FIGURE 5.4

Reactor Core and Primary Shield Components

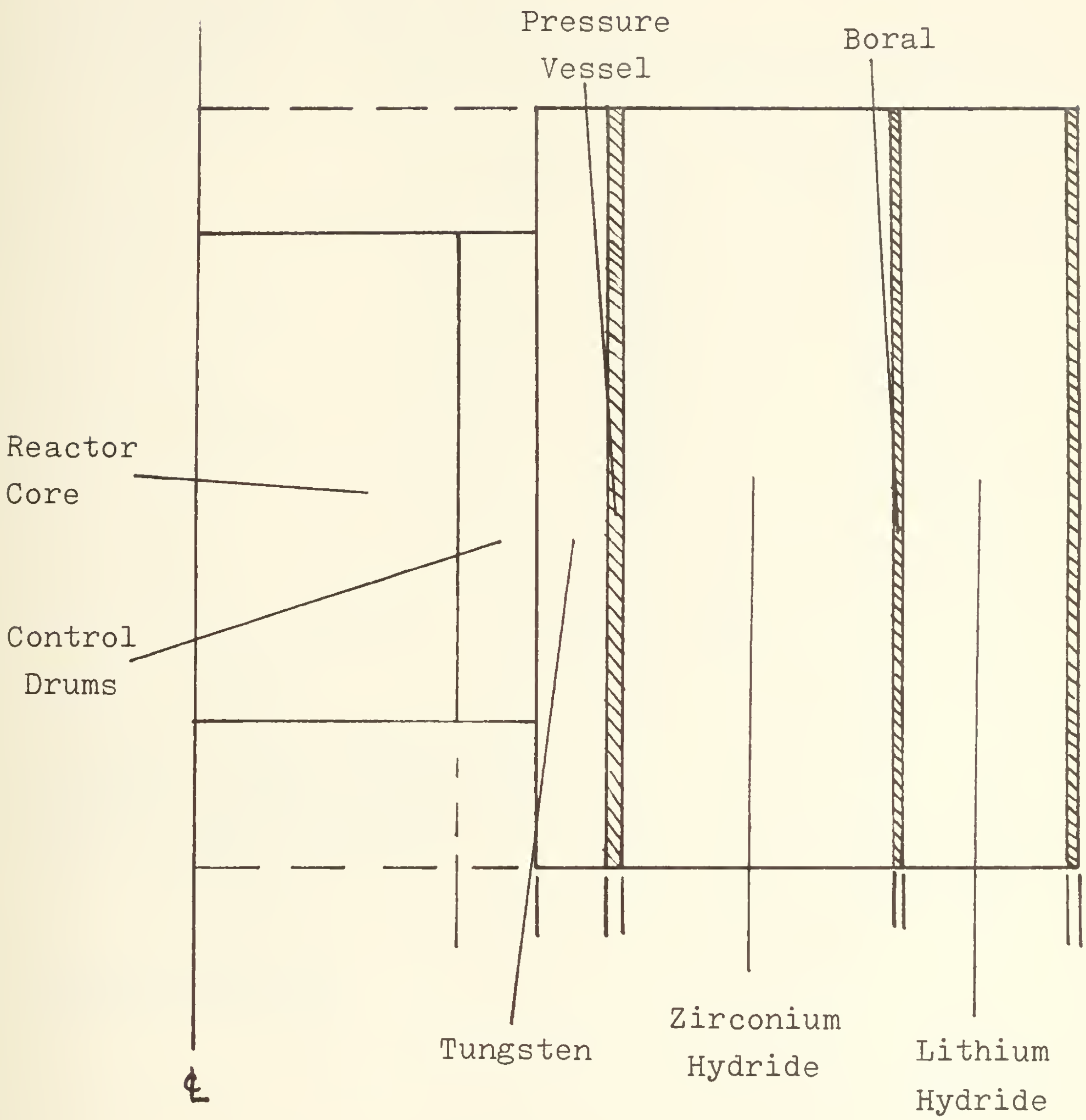


TABLE 5-4

PRIMARY SHIELD DIMENSIONS

(1 MR/HR)

REACTOR POWER = 524.85 MW

SHIELD DESIGN 1 MR/HR AT 20 FEET FROM RX CENTERLINE

ITEM	RI (IN)	RO (IN)	WEIGHT (LBS)
TUNGSTEN	38.45	46.52	144824.
PRESSURE VESSEL	46.52	48.02	30056.
ZIRCONIUM HYD	48.02	79.02	594923.
LITHIUM HYDRIDE	79.27	98.82	88121.
SHIELD TANK	98.82	99.32	30864.
PLUG SHIELD			61791.

TOTAL SHIELD WEIGHT = 950577. (LBS)

OVERALL LENGTHS

PRESSURE VESSEL =154.76 IN
ZIRCONIUM HYDRIDE =216.76 IN
LITHIUM HYDRIDE =256.36 IN
SHIELD TANK =257.36 IN

CORE DIMENSIONS

RADIUS =29.30 IN
LENGTH =52.74 IN

TABLE 5-5
PRIMARY SHIELD DIMENSIONS
(10 MR/HR)

REACTOR POWER = 524.85 MW

SHIELD DESIGN 10 MR/HR AT 20 FEET FROM RX CENTERLINE

ITEM	RI (IN)	RO (IN)	WEIGHT (LBS)
TUNGSTEN	38.45	45.37	125952.
PRESSURE VESSEL	45.37	46.87	28964.
ZIRCONIUM HYD	46.87	77.87	578074.
LITHIUM HYDRIDE	78.12	90.97	53211.
SHIELD TANK	90.97	91.47	26993.
PLUG SHIELD			61791.

TOTAL SHIELD WEIGHT = 874986. (LBS)

OVERALL LENGTHS

PRESSURE VESSEL =153.61 IN
ZIRCONIUM HYDRIDE =215.61 IN
LITHIUM HYDRIDE =241.81 IN
SHIELD TANK =242.81 IN

CORE DIMENSIONS

RADIUS =29.30 IN
LENGTH =52.74 IN

exchangers, and a reasonable allowance for access for maintenance. This determined the containment inside diameter which was 36.7 feet for the 1 MR/HR case and 35.4 feet for the 10MR/HR case. The thickness was determined as described in Chapter 4 and was approximately 3" for the 1000 ft submergence design case. Figure 5.5 is a sketch of the containment. It is assumed that the containment vessel will have sufficient means of access in the form of bolted access doors. It will also have provisions for removing all or part of the elliptical top for refueling and major repairs to the core or primary heat exchangers and fission product cleanup system. The material for the containment is assumed to be a mild steel with a yield strength of 50,000 psi.

The resulting containment was not stiffened, but was still felt to give a conservative estimate of the containment weight. The actual containment would undoubtedly be a ring stiffened shell, similar to submarine pressure hulls. If a high strength steel such as HY-80 were used as the construction material, the resulting containment thickness would be about 1.9". Including the stiffener web and flange, an equivalent shell thickness would be approximately 2.5", which is less than the present 3" and would result in a lighter, but certainly more expensive containment. Figure 5.5 is a sketch of the unstiffened 3" containment, with overall dimensions. Although it appears almost spherical, there is a 9 foot cylindrical section in the center. The calculations used to determine the containment size are found in Appendix D.

FIGURE 5.5a Containment (Reactor & PRI-HX)

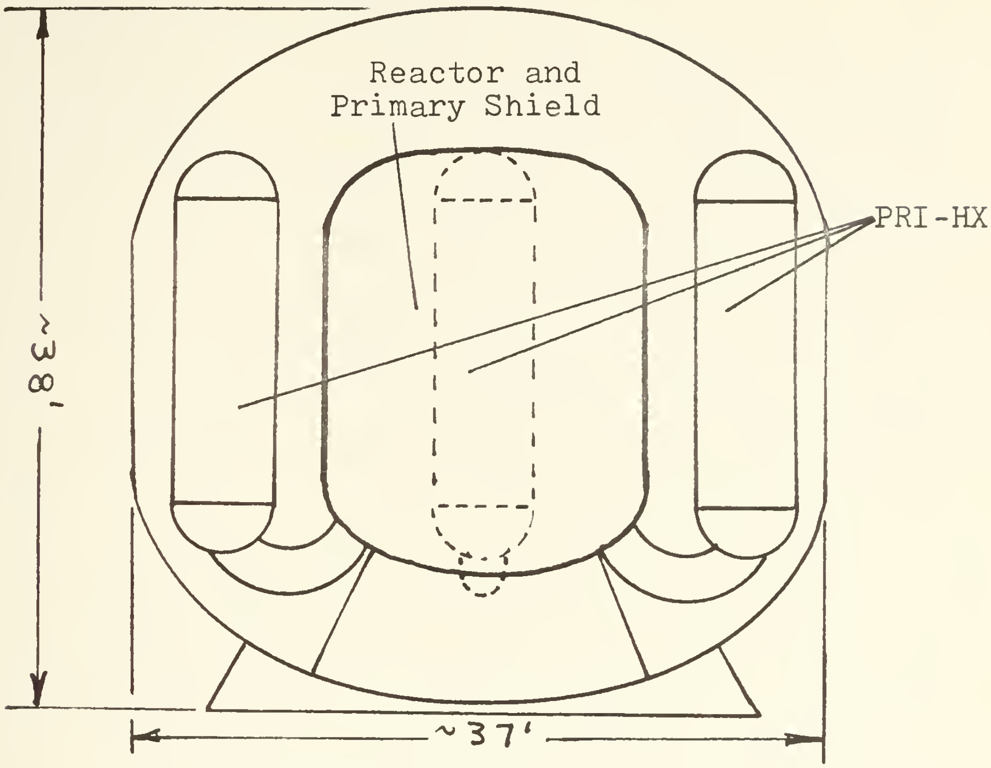
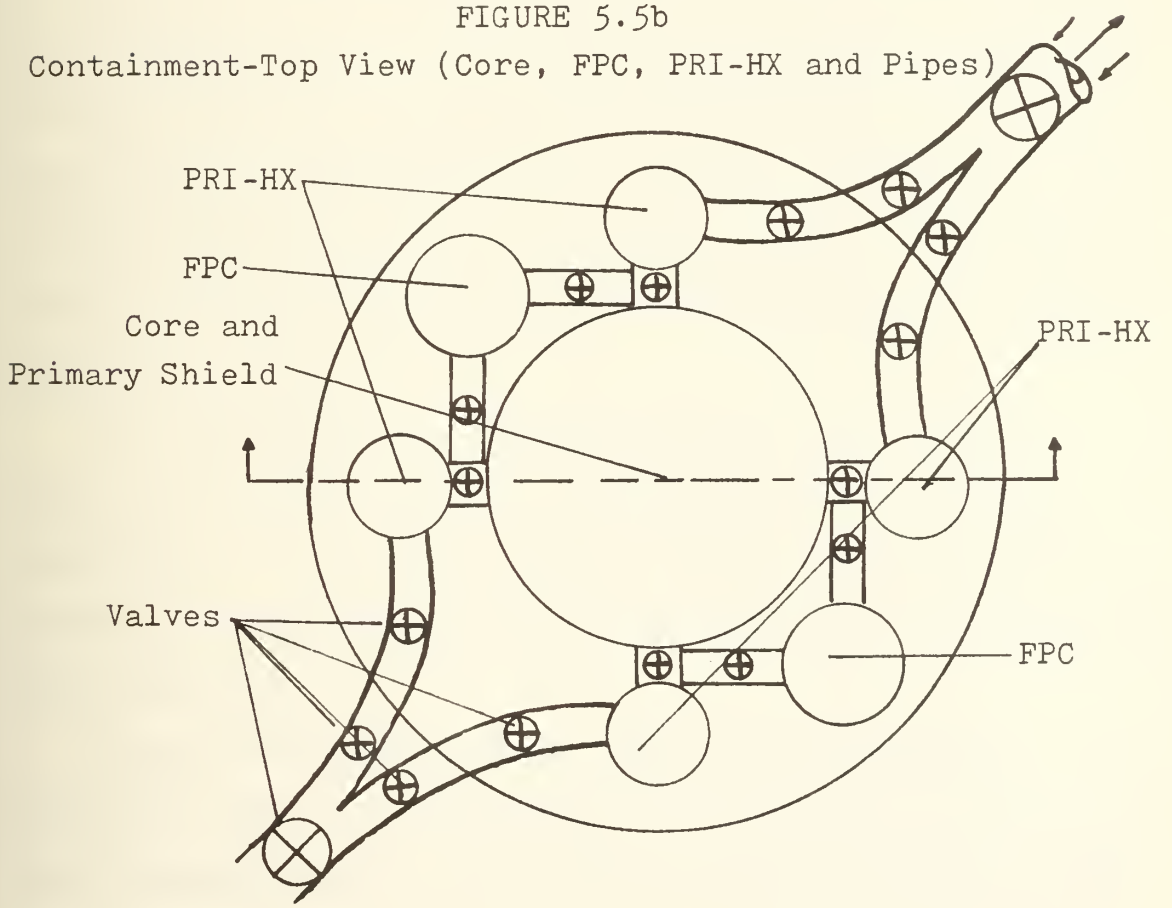


FIGURE 5.5b
Containment-Top View (Core, FPC, PRI-HX and Pipes)



5.5 Other Power Plant Components

As mentioned in Chapter 4, the only system components that were investigated in detail were the shield, and heat exchangers. All others were to remain as Westinghouse has described them. These "other" items were scaled according to scaling relationships deduced from Westinghouse Data (Appendix D). There were some overlapping cases that were considered individually, such as the T-C-Hx and the Fission Product Cleanup system. For the former, an estimate of the turbomachinery contribution to the total T-C-Hx weight in the Westinghouse baseline was made. This weight was then scaled to higher power levels for the modified concept. The heat exchanger (Hx) portion was calculated directly, and appears as a separate entry in the eventual system weight breakdown. The same was true of the FPC which was originally included with the WANL secondary shield. For the modified plant the secondary shield was the containment, and was calculated directly, the FPC was scaled up using Westinghouse weight information (T 3).

The scaling itself (Appendix D) was done using a log-log plot of the weights of the individual baseline components for two power levels, 140,000 and 225,000 SHP. The resulting equations are felt to represent the Westinghouse predictions well.

Since the modified power plant now has separated components, there is considerable piping, and propulsion plant operating fluids that require weight estimates. This

was done using pipe sizes and weights as well as fluid weights per foot of pipe. This information was one of the outputs of HXSIZE, and assumes a velocity in the individual pipe of twice the velocity of that fluid in the respective heat exchanger. The higher the fluid velocity, the smaller the pipe diameter becomes for a given mass flow rate. For a fixed pressure level in the pipe, the pipe wall thickness is directly proportional to the diameter. There is some optimum choice of pipe diameter and hence weight, and the resulting higher fluid velocities, friction pressure drop, and pumping power. This study did not attempt to optimize these parameters. The calculations concerning piping and propulsion plant operating fluid weights are in Appendix D.

All propulsion plant auxiliaries, including control systems, cryogenic refrigerators, the above mentioned piping and fluids, fresh water and salt water pumps, as well as the primary shield cooling system are included in the weight category "WATER AND AUXILIARY SYSTEMS".

A 50% increase in Control gas storage and Helium inventory was assumed. These weights were therefore higher than the same categories for the Westinghouse concept. These increases were to account for the existence of two separate systems, one for the primary system, and one for the secondary system.

An important item that is not determined directly is valve weights. Although the modified plant has different types and undoubtedly more valves than the Westinghouse

baseline, no attempt was made to determine their number or weights. It is assumed that valve weights are included in "Water and Auxiliary Systems". This category for the modified power plant exceeds the estimates for the Westinghouse baseline by over 100,000 lbs.. This was felt to be sufficient to include the weights of valves, and other changed items.

5.6 Weight Estimates

Table 5-6 lists the final estimated weight account for the 231,000 SHP modified power plant. The two cases are for 10 MR/HR and 1 MR/HR, essentially at the exterior of the containment. The results indicate that the 10 MR/HR configuration (specific weight - 15.0 lbs/shp) slightly exceeds the design goal from Figure 2.1 (14.8 lbs/shp). The 1 MR/HR case is slightly heavier, entirely due to the thicker shield, and slightly larger containment. At 15.6 lbs/shp it is within the "design lane" (14.8 - 17.0 lbs/shp) and is much preferrable from a personnel radiation exposure standpoint.

Table 5-6 includes weight categories for the Waterjet propulsors, which include the inlet and outlet ducting weights as well as water in the system, and also the Lift Fan weights. Neither of these were included in the Westinghouse weight summary because, of necessity, their system was designed to be independent of the modes of propulsion and lift as well as the relative power distribution between lift and propulsion. The weights were included here

	10 MR/HR		1 MR/HR	
	WEIGHT (1000 lbs)	(LBS/SHP)	WEIGHT (1000 lbs)	(LBS/SHP)
Reactor	32	0.1	32	0.1
Primary Shield	875	3.8	951	4.1
Turbine - Compressors	46	0.2	46	0.2
Heat Exchangers (including fluids)	756	3.3	756	3.3
Control Gas Storage	74	0.3	74	0.3
Emergency Cooldown	8	-	8	-
Helium Inventory	3	-	3	-
Containment	545	2.4	606	2.6
Fission Product Cleanup	72	0.3	72	0.3
Water and Auxiliary Systems	400	1.7	400	1.7
Power Transmission	253	1.1	253	1.1
Waterjets (including water)	350	1.5	350	1.5
Lift Fans	40	0.2	40	0.2
	3454	15.0	3591	15.6

Table 5-6

WEIGHT SUMMARY - 231,000 SHP INDIRECT CYCLE

for two reasons. First, they are properly included in the definition of propulsion plant weight (Chapter 2). Secondly, the propulsion plant was designed for a specific ship, where these weights had been previously estimated (C2).

Table 5-7 is a weight summary for a 231,000 SHP power plant using estimates of Westinghouse weight items. For this summary, the same Waterjet and Lift system weights have been added, as described above. On a total system basis, the modified indirect cycle plant is

- 35% higher than WANL for 10 MR/HR,
- 24% higher than WANL for 1 MR/HR.

If one omits the Waterjet and Lift fans, the modified plant is

- 41% heavier for the 10 MR/HR case,
- 28% heavier for the 1 MR/HR case.

5.7 Summary

Figure 5.6 indicates the relative position in the "design lane" of Chapter 2 of the power plant specific weight for both the 10 MR/HR and 1 MR/HR cases. Several conclusions can be reached concerning the modified concept.

- It is within the "design lane" for the baseline SES.
- It is heavier than the Westinghouse Direct cycle concept.
- It occupies more volume than the Westinghouse concept.
- It has a lower efficiency than the reference baseline power plant (32.8% vs. 35.7%).

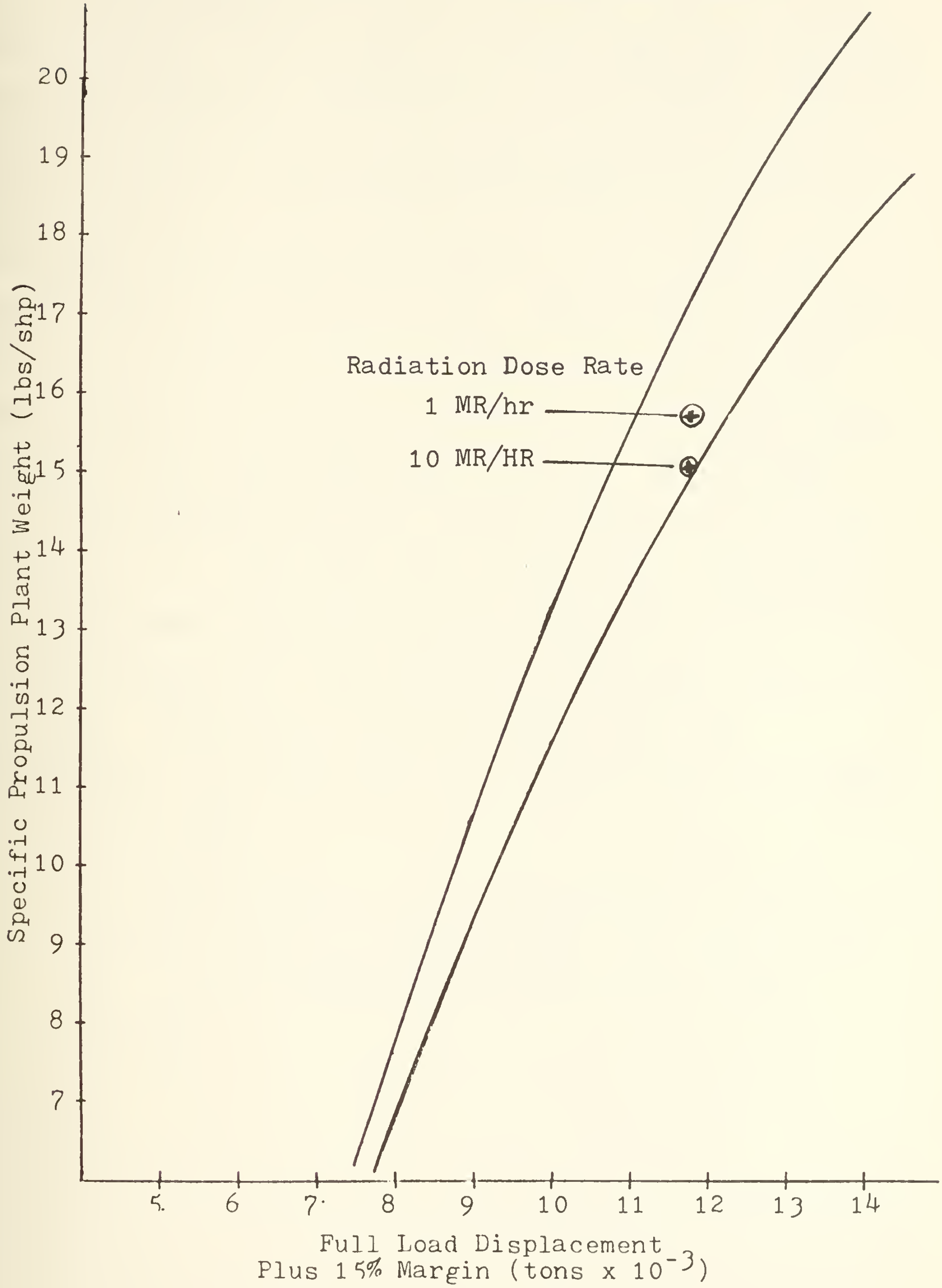
	10 MR/HR		1 MR/HR	
	WEIGHT (1000 lbs)	(LBS/SHP)	WEIGHT (1000 lbs)	(LBS/SHP)
Reactor	32	0.1	32	0.1
Shield	780	3.4	923	4.0
T-C-Hx	162	0.7	162	0.7
Control Gas Storage	49	0.2	49	0.2
Emergency Cooldown	8	-	8	-
Helium Inventory	2	-	2	-
Equipment Shield & Fission Product Cleanup	585	2.5	792	3.4
Water and Auxiliary Systems	295	1.3	295	1.3
Power Transmission	253	1.1	253	1.1
Waterjets (including water)	350	1.5	350	1.5
Lift Fans	40	0.2	40	0.2
	2556	11.1	2906	12.6

Table 5-7

WEIGHT SUMMARY - 231,000 SHP DIRECT CYCLE

FIGURE 5.6

Specific Weight vs. Full Load Displacement



Although the size of the containment is rather large, it could be made smaller by using a different type of primary heat exchanger, such as plate fin rather than shell and tube. This could result in a smaller size heat exchanger, but might also create new problems of maintaining system integrity under the high operating temperatures and pressures. The containment could also be made smaller by allowing less internal room for maintenance etc.. This change would only result in a slightly smaller diameter, and possibly lower overall height, as well as a reduction in containment weight. It was felt that this high L_C/B_C SES was an extreme case (i.e. most SES designs favor lower L_C/B_C ratios by at least a factor of 2). This means that for the same displacement, the length would be shorter and the beam wider. With the present configuration, two reactors athwartships, there is no problem. Therefore it can be assumed that this configuration would also "fit" in a lower L_C/B_C ship. Hence one can state that:

- The proposed power plant dimensions and volume do not adversely affect the baseline SES. The power plant will fit in the propulsion system volume design envelope.

Chapter 6

POWER PLANT COMPARISONS

This chapter will attempt to list possible advantages, as well as disadvantages that the Indirect Cycle power plant has when compared to the Westinghouse baseline power plant.

6.1 Advantages of Indirect Cycle

The opinions found in this section are those developed by the author during this study. Westinghouse has studied an Indirect Cycle power plant and they may have reached quite different conclusions.

Item	Comment
1. T-C-Hx	a) outside containment. b) accessible. c) easier to maintain. d) lower maintenace costs. e) units separated in space.
2. Primary system	a) simpler. b) fewer things inside containment. c) possibly higher reliability. d) no lubricating fluids to contaminate primary system.
3. Heat exchangers	a) accessible. b) larger tubes, less chance of plugging. c) easier to maintain.

Item	Comment
	d) need not be designed to nuclear standards.
3. Primary/Secondary systems	a) T-C-Hx do not "see" radioactive fission products.
	b) Reactor partially decoupled from secondary system transients.
	c) can isolate secondary system from outside containment.
4. Containment penetrations	a) no water inside containment - reduces chance of accidental core flooding.
	b) fewer penetrations.
5. Large containment volume	a) lower containment pressure if pipe ruptures in Primary system.
	b) more access for maintenance.
	c) larger "dead" space between core and external environment (missiles/collision).
	d) personnel cannot get as close to core during operation (lower absorbed dose).
6. Prototype experience	a) closed cycle machinery layout like Oberhausen II.
	b) could go to direct cycle in second generation.
7. Weight	a) total system weight is acceptable for baseline SES.

6.2 Disadvantages of Indirect Cycle

Item	Comment
1. Weight	a) total system weight is 24-35% heavier than WANL.
2. Volume	a) total system volume is considerably larger than WANL.
3. Efficiency	a) overall cycle efficiency is lower, 32.8% vs 35.7%.
4. Components	a) more components.
	b) still have some items inside containment.
5. Primary - Heat Exchanger	a) high temperatures.
	b) high pressures.
	c) could be a weak link in system.
6. Control	a) two systems, primary and secondary.
	b) more variables to monitor and control.
	c) control systems could be more complex.
7. Secondary system	a) system more susceptible to Helium leakage to atmosphere.
	b) Secondary system rupture could cause serious problems in both primary and secondary systems.

6.3 Discussion

The items listed in the previous two sections were an attempt by the author to express qualitatively some of the fundamental differences between the Indirect Cycle, and the

Westinghouse Direct cycle concept. No attempt was made to compare this system with a PWR, since because of the weight differential it appears that a PWR is not a candidate for the SES. There are some similarities between the Helium cooled Indirect Brayton cycle, and Pressurized Water Reactors. These could be classified as functional or operational similarities and include:

- Both are Indirect cycles.
- Both require two control systems.
- During power operation the primary system is inaccessible.
- Secondary system pipe rupture will cause similar core thermal transients, and could necessitate emergency core cooling.
- Secondary system is accessible and maintainable soon after reactor shutdown.

Any similarities probably end at that point, and certainly no statements concerning similarity between development costs, operability, controllability, safety, etc. can be made. In short, the modified power plant still has many of the areas of technical risk that the Westinghouse concept has. These areas include:

- Core flooding - although water is physically not present in the containment, the chance of collision and possible sinking still remains.
- Superconducting Machinery Development

- Fission product retention - in the modified concept it would have less of an effect on the total system. Although good fission product retention is desirable, it would not be absolutely essential.
- Reliability/Maintainability/Availability - although the primary system is simpler, and the secondary system is accessible, there is now an additional control system as well as a high temperature/high pressure heat exchanger to consider. The author suggests that the new concept would have a higher availability; Westinghouse, in studying an Indirect cycle concluded that it would have a lower availability.
- Ruggedness - This area is one that, of necessity, must be designed into a system from the start. The author can make no claim about the ruggedness of this concept. Westinghouse claims that their concept, designed with ruggedness in mind, can withstand accelerations of about 40 g's with only minor modifications. This area could be a potential stumbling block for light weight nuclear systems if it were to cause the individual components to become more massive, and hence heavier.
- Operability - The concept must be operable by ship's company. Although automatic control is understandable for such a complex system, from a safety standpoint it must be highly reliable and "understandable". This

high reliability would include such things as a 2 out of 3 High Integrity Voting System (HIVS) for monitoring system parameters and making critical decisions. As for "understandable", as an extreme case, if graduate engineers were required in order to understand and operate the plant, the system could never be used on a Navy ship.

- Cost - As mentioned before, cost is usually the final tool in the decision making process. If the costs are predicted to be excessive, no one will ever consider the concept. However, as discussed in Chapter 3, the long range military or commercial worth to the nation, as determined in a cost-benefit analysis, might be quite high. In this case the cost to not develop the system might be higher.

Nothing has been said in this work concerning other possible uses of high temperature gas cooled reactors. Some of these uses include process heat for commercial users, power plants combining electrical generation and district heating, etc. Any of these development avenues could help to distribute the costs of reactor plant research and development, if similar type components were to be used.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Results

The following is a list of conclusions that have been reached during this work.

1. The modified power plant - Indirect Brayton cycle - does meet the weight and volume restrictions of the baseline SES. The design goal and upper limit for the propulsion plant specific weight is

   - Design goal 14.8 lbs/shp,
   - Upper limit 17.0 lbs/shp.

   The results for the proposed power plant, for the specified radiation dose rates at 20 feet from the reactor centerline are

   - 10 MR/HR Dose rate - 15.0 lbs/shp,
   - 1 MR/HR Dose rate - 15.6 lbs/shp.

2. The modified power plant weighs more, and occupies more volume than the Westinghouse reference design. The complete propulsion plant specific weights for the reference design are estimated to be,

   - 10 MR/HR Dose rate 11.1 lbs/shp
   - 1 MR/HR Dose rate 12.6 lbs/shp

   When the Indirect cycle is compared with the reference design, on the total plant weight basis, the Indirect cycle is heavier by the following amounts,

   - 10 MR/HR Dose rate 35% heavier,

- 1 MR/HR Dose rate 24% heavier.

If the basis is the Nuclear subsystem only, the percentages are

- 10 MR/HR Dose rate 41% heavier,
- 1 MR/HR Dose rate 28% heavier.

3. The modified power plant has a lower overall efficiency, than the Westinghouse baseline concept (32.8% vs. 35.7%).

4. There are several areas of technical risk that affect both this Indirect cycle plant, and the reference design. These include:

   - Superconducting generators, motors, power distribution systems and auxiliaries.
   - High power density core and its associated long life.
   - Fission product retention.
   - Core flooding.
   - High temperature Helium environment effects on materials.
   - Control system reliability.
   - Total system availability.
   - Riggedness in ocean environment.
   - Operability by Navy crew.

In considering all of the above, for this application (large SES) it is concluded that the modified power plant is preferrable to the direct cycle reference baseline. This is due primarily to maintenance and fission product retention

considerations. For more demanding applications (volume limited ships), the Westinghouse concept may be preferrable for entirely different reasons than those indicated above. However, a redesign of the modified power plant that could reduce containment size might be competitive with the Westinghouse concept from a volume standpoint. It is felt that the modified power plant would then be preferrable for all applications.

7.2 Suggestions for Future Work

All of the foregoing conclusions depend on the basic assumption that those items not examined in this study remained as Westinghouse described them. The following are areas that merit further study.

1. Core design - A redesign of the core, perhaps to the same power density goal, should be performed. This should be done from a reactor physics standpoint to incorporate an in-core poison for the core flooding case. It should also be done from a thermal-hydraulics standpoint to optimize pressure and temperature conditions in the core.
2. Reoptimization of the cycle. This Indirect cycle utilized many of the same parameters, i.e. core exit temperature and pressure, pressure drops in heat exchangers, etc. as used in the Westinghouse direct cycle study. An optimization of an indirect cycle for this specific application could result in a more

compact, more efficient plant.

3. Shield Design - If the core is redesigned, the shield must also be redesigned. Since the shield and containment comprise a large fraction of the total system weight (slightly more than 40% for the Indirect cycle), increased core volume and hence shield volume could rapidly drive up the propulsion plant weight.
4. Consider the possible use of lower pressures for both the primary and secondary systems. Pressure has an effect on piping and heat exchanger design. The higher the pressure, the heavier the equipment. Lower pressures suggest lower efficiencies, requiring larger power plants for the same desired output. There may be an optimum pressure level that can serve as a balance between efficiency and weight.
5. Perform a Reliability/Maintainability/Availability Analysis of the Indirect cycle plant. Detailed design information and modes of operation would be necessary before this could be attempted. In addition, component failure data would also be required. An approach similar to that used in WASH-1400, that used Failure Modes and Effects Analysis (FMEA) (U2) and the use of Fault trees and Event trees would be preferrable. This would give an indication of weak points in the design by singling out possible common mode failures.
6. Study the structural effects on the ship of installing

a large nuclear power plant, including the effects of nuclear plant point landings, and foundation weights on the total ship structure.

7. Study the impact of imposing vibration/shock hardness/ ruggedness constraints on the nuclear power plant.
8. Study the impact of a lower power density, lower temperature level on core life and total system reliability. This could be done for both the Direct cycle and Indirect cycle.

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Appendix A

INDIRECT BRAYTON CYCLE

The reasons for choosing an Indirect Brayton Cycle (Primary/Secondary systems) have already been discussed. This appendix will detail the calculational steps involved, and describe the inputs to the computer code written to perform the cycle calculations.

The state points for the chosen cycle are as indicated in Figure A.1. The basic assumptions were that the helium gas was considered to be ideal, with a specific heat (C_p) of 1.241 BTU/lbm ^oR, and specific heat ratio (γ) of 1.66.

A.1 Individual Components

The components described here are turbines, compressors, and heat exchangers.

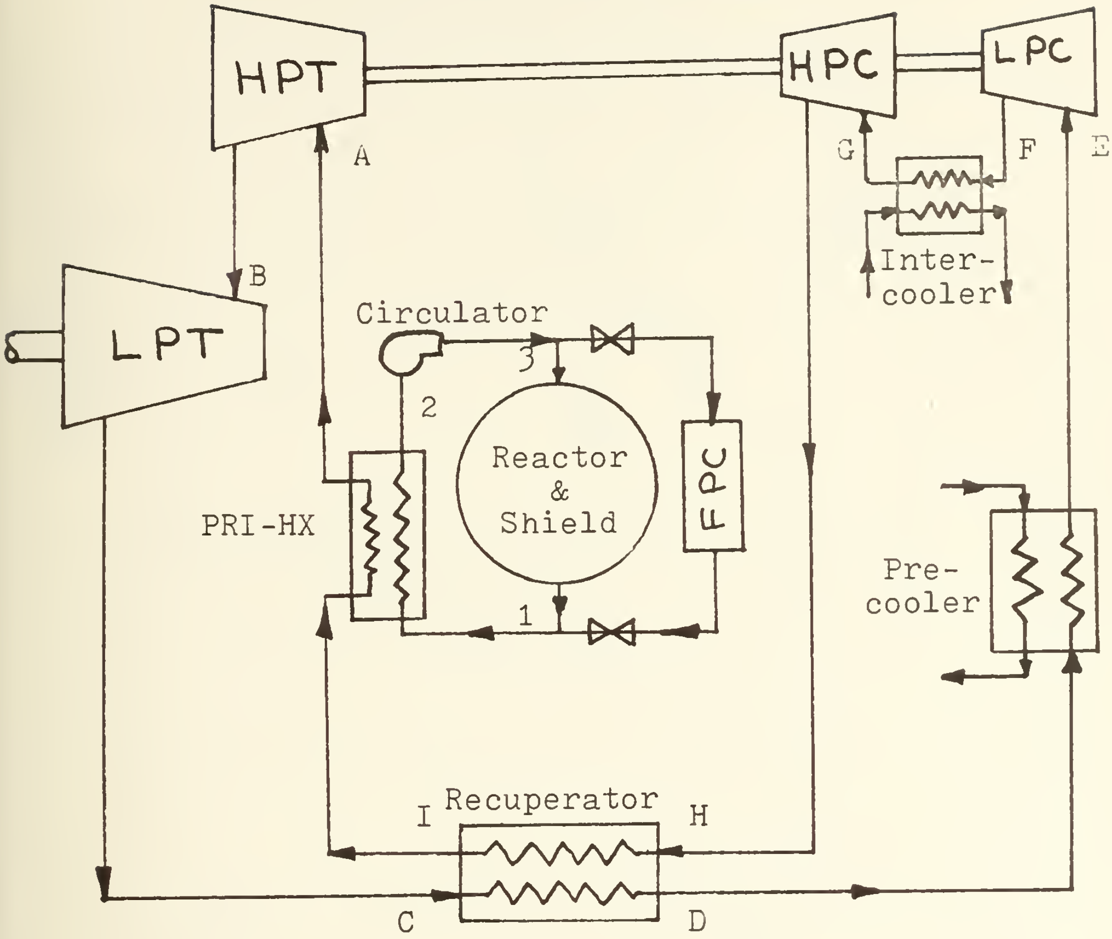
A.1.1 Real Turbines

For turbines operating between temperatures T_α and T_β at pressures of P_α and P_β , the turbine work is defined as

$$\dot{W}_T = \dot{m}C_p \ (T_\alpha - T_\beta). \tag{A.1}$$

Figure A.2 is a sketch of a T-S diagram indicating a real turbine operating between points α and β . If the turbine expansion is 100% efficient, the turbine expansion is called isentropic, and the final state is at βs. In order to describe the departure from the ideal turbine the term "isentropic efficiency" has been defined as,

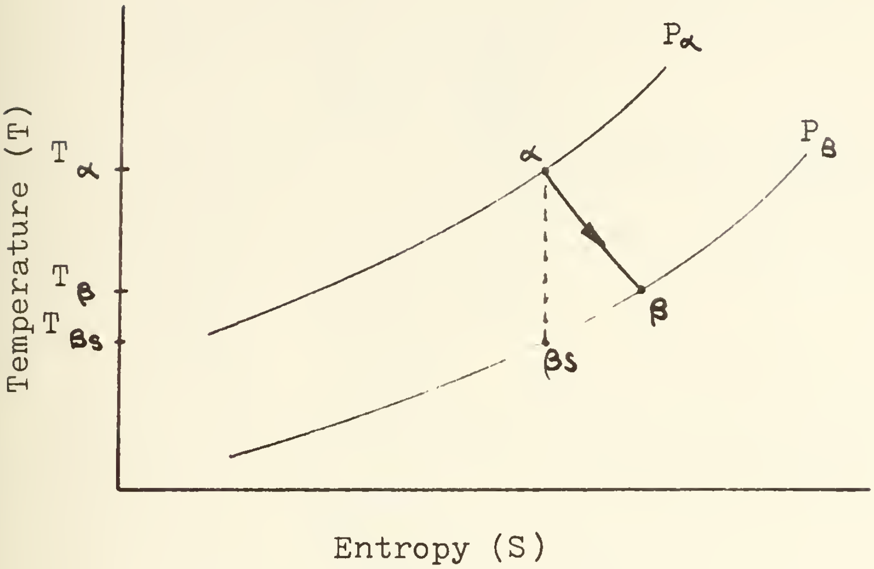
FIGURE A.1
INDIRECT BRAYTON CYCLE



State Point	Description
1	Reactor Outlet (Primary Loop)
2	PRI-HX Outlet (Primary Loop)
3	Circulator Outlet/ Reactor Inlet
A	HP Turbine Inlet (HPT)
B	LP Turbine Inlet (LPT)
C	Recuperator Inlet - hot side
D	Recuperator Outlet - hot side
E	LP Compressor Inlet (LPC)
F	Intercooler Inlet
G	HP Compressor Inlet (HPC)
H	Recuperator Inlet - cold side
I	PRI-HX Inlet (secondary loop side)

FIGURE A.2

Turbine Temperature-Entropy (T-S) Diagram



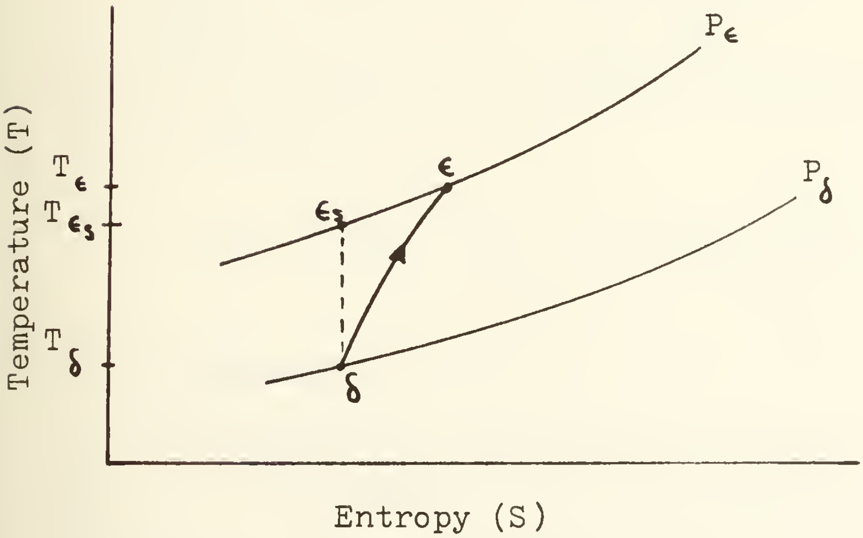


FIGURE A.3

Compressor Temperature-Entropy (T-S) Diagram

$$\eta_T = \frac{W_T,\ \text{real}}{W_T,\ \text{ideal}} . \tag{A.2}$$

for constant specific heat, equation (A.2) becomes,

$$\eta_T = \frac{(T_\alpha - T_\beta)}{(T_\alpha - T_{\beta s})} . \tag{A.3}$$

Now for an isentropic expansion there is a relationship between T_α and $T_{\beta s}$ given by

$$\left(\frac{T_\alpha}{T_{\beta s}}\right) = \left(\frac{P_\alpha}{P_\beta}\right)^{\frac{\gamma-1}{\gamma}} , \tag{A.4}$$

where γ is the specific heat ratio (C_p/C_v). Solving for $T_{\beta s}$ one finds,

$$T_{\beta s} = \frac{T_\alpha}{(P_\alpha / P_\beta)^{(\gamma-1)/\gamma}} . \tag{A.5}$$

Combining equations (A.1), (A.3) and (A.5), the actual turbine work is

$$\frac{\dot{W}_T}{\dot{m} C_p} = \eta_T T_\alpha \left(1 - \left(\frac{1}{P_\alpha / P_\beta}\right)^{\frac{\gamma}{\gamma-1}} \right). \tag{A.6}$$

T_β can be solved for by combining equations (A.3) and (A.5) to give,

$$T_\beta = T_\alpha \left[1 - \eta_T \left(1 - \left(\frac{1}{P_\alpha / P_\beta}\right)^{\frac{\gamma}{\gamma-1}} \right) \right] . \tag{A.7}$$

A.1.2 Compressors

The development for real Compressors is similar to that for real turbines. The T-S diagram for a real compressor is sketched in Figure A.3. The work input to the compressor is,

$$\dot{W}_c = \dot{m}\, C_p\, (T_\epsilon - T_\delta). \tag{A.8}$$

The isentropic compressor efficiency is defined as

$$\eta_c = \frac{W_{out},\ \text{ideal}}{W_{in}} \qquad \text{(A.9)}$$

An isentropic compression process between points δ and ϵ_s is given by,

$$\left(\frac{T_{\epsilon s}}{T_\delta}\right) = \left(\frac{P_\epsilon}{P_\delta}\right)^{(\gamma-1)/\gamma}. \qquad \text{(A.10)}$$

T_ϵ can be determined from equations (A.9) and (A.10) in terms of T_δ and (P_ϵ/P_δ) as

$$T_\epsilon = T_\delta\left[1 + \frac{1}{\eta_c}\left(\left(\frac{P_\epsilon}{P_\delta}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \qquad \text{(A.11)}$$

Substituting for T_s and combining equations (A.8) and (A.11) gives,

$$\dot{W}_c = \dot{m}\, Cp\, \frac{T_\delta}{\eta_c}\left[\left(\frac{P_\epsilon}{P_\delta}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad \text{(A.12)}$$

A.1.3 Heat Exchanger Effectiveness

The heat exchanger effectiveness, is properly called "temperature effectiveness", since it relates the maximum or minimum temperatures on one side of the Hx to those on the other. Figure A.4 is a sketch of a counterflow, shell and tube heat exchanger. Figure A.5 is a plot of the corresponding temperatures on the shell (1) and tube (2) side fluids, as a function of length in the heat exchanger. The effectiveness, ϵ, is defined as,

$$\epsilon = \frac{C_h}{C_{min}}\frac{(T_{1i} - T_{1o})}{(T_{1i} - T_{2i})} = \frac{C_c}{C_{min}}\frac{(T_{2o} - T_{2i})}{(T_{1i} - T_{2i})}. \qquad \text{(A.13)}$$

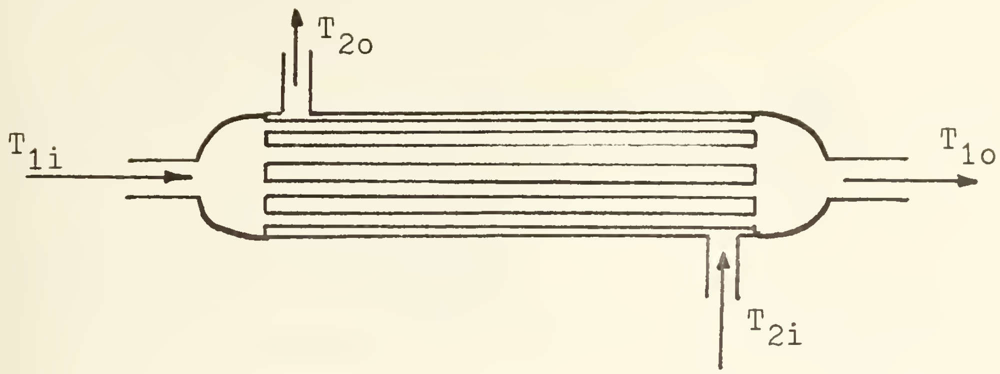


FIGURE A.4
Counter-flow Shell and Tube Heat Exchanger

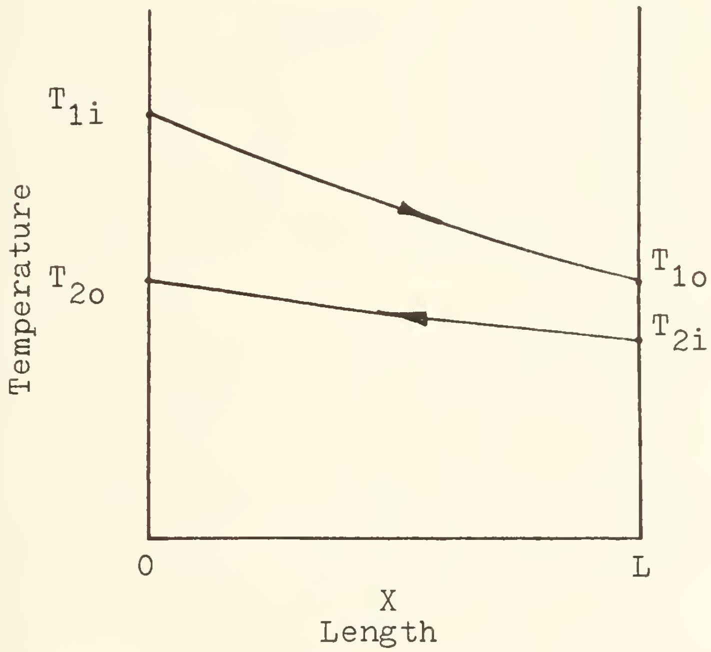


FIGURE A.5
Heat Exchanger Temperature-Length Diagram

C_h is defined for the "hot" fluid as,

$$C_h = \dot{m}_h \, C_{p_h} \ , \qquad \text{(A.14)}$$

and C_c is similarly defined for the "colder" of the two fluids. C_{min} is the smaller of C_h and C_c.

A.2 Computer Code Development

The basic computer code is written in FORTRAN IV. It combines the equations derived above with an equation for reactor power,

$$\dot{Q}_R = \dot{m}_p \, C_p \, (T_1 - T_3), \qquad \text{(A.15)}$$

and the 1st Law of Thermodynamics,

$$Q + W = 0 \ , \qquad \text{(A.16)}$$

to determine cycle state points, overall cycle efficiency, and system flow rates.

Besides the basic assumptions listed above the following additional assumptions are inherent in the code,

1) The H.P. compressor work is equal to the L.P. compressor work, the sum of which equals the H.P. turbine work.

2) The primary system flow rate is equal to the secondary system flow rate.

3) The primary system circulator receives its power from the L.P. turbine, and hence lowers the net work output of the L.P. turbine.

4) Compressor inlet temperatures are the same for each compressor.

5) The compressor pressure ratios (P_{out}/P_{in}) are the

same for each compressor.

6) Mass flow rates in both primary and secondary systems are constant.

A.3 Computer Code Inputs

The following are a list of code inputs, in the order they are input. For input format specification, refer to the code listing.

Input	Definition
WOUTS	Desired net output (SHP).
T1	Reactor outlet temperature (^oR).
P1	Reactor outlet pressure (PSIA).
T3	Reactor inlet temperature (^oR).
DPRX	Reactor pressure drop (PSIA).
DHPRI	Pressure drop, PRI-Hx Primary side (PSIA).
PA	H.P. turbine inlet pressure (PSIA).
PB	H.P.turbine outlet pressure (PSIA).
TG	Intercoolers Helium outlet temperature (^oR).
TE	Precooler Helium outlet temperature (^oR).
DPPRI	Pressure drop, PRI-Hx Secondary side (PSIA).
DPRECH	Pressure drop, Recuperator Hot side (PSIA).
DPPRE	Pressure drop, Precooler (PSIA).
DPINT	Pressure drop, Intercooler (PSIA).
DPRECC	Pressure drop, Recuperator Cold side (PSIA).
CP	Specific heat, constant pressure (BTU/lb^{o}R).
ETAT	Isentropic turbine efficiency.
ETAC	Isentropic compressor efficiency.
EFPRI	Primary heat exchanger effectiveness.
GAMMA	Specific heat ratio (C_p/C_v).

```
*****************************************************
*                                                   *
*      INDIRECT BRAYTON CYCLE COMPUTER CODE         *
*                                                   *
*****************************************************


      REAL*4 MPMS,MS,MP
      DATA KI,KO/ 5,6 /
      TURB(X,Y,Z)=(1.-X*(1.-(1./Y)**Z))
      COMP(X,Y,Z)=(1.+1./X*(Y**Z-1.))
      TLC(X,Y,Z)=X-(X-Y)/Z
      EFF(X,Y,Z)=(X-Y)/(Z-Y)
      READ(KI,3) WCUTS
    3 FORMAT(F10.0)
      READ(KI,5) T1,P1,T3,DPRX,DHPRI
    5 FORMAT(5F10.4)
      READ(KI,11) PA,PB,TG,TE
   11 FORMAT(4F10.4)
      READ(KI,1) DPPRI,DPRECH,DPPRF,DPINT,DPRECC,CP
    1 FORMAT(6F10.4)
      READ(KI,11) ETAT,ETAC,EPPRI,GAMMA
      P3=P1+DPRX
      P2=P1-DHPRI
      P3P2=P3/P2
      Z=(GAMMA-1.)/GAMMA
      T2=T3/COMP(ETAC,P3P2,Z)
      TI=TLC(T1,T2,EPPRI)
      MPMS=1.0
      TA=TI+MPMS*(T1-T2)
      WRITE(KO,2)TA,PA,PB,TG,TE,T2
      WRITE(KO,2)DPPRI,DPRECH,DPPRF,DPINT,DPRECC,CP
      WRITE(KO,2)ETAT,ETAC,EPPRI,GAMMA
    2 FORMAT('0',6F15.4)
   10 PAPB=PA/PB
      TB=TA*TURB(ETAT,PAPB,Z)
```

```
      PEPE=(1.+(ETAC*ETAT*TA*(1.-(1./PAPB)**Z))/(2.*TP))**(1./Z)            IBCC0037
      PI=PA+DPPPT                                                           IBCC0038
      PH=PI+DPPFCC                                                          IBCC0039
      PG=PH/PFPF                                                            IBCC0040
      PF=PG+DPINT                                                           IBCC0041
      PE=PF/PFPF                                                            IBCC0042
      PD=PE+DPPFE                                                           IBCC0043
      PC=PD+DPPFCH                                                          IBCC0044
      PBPC=PB/PC                                                            IBCC0045
      TC=TB*TUPB(ETAT,PBPC,Z)                                               IBCC0046
      SCIRCW=CP*(T3-T2)*MPMS                                                IBCC0047
      SHPT=CP*(TA-TB)                                                       IBCC0048
      SLPT=CP*(TB-TC)-SCIRCW                                                IBCC0049
      WOUTM=WOUTS/1.34104E03                                                IBCC0050
      MS=(WOUTS/1.413926)/SLPT                                              IBCC0051
      MT=MPMS*MS                                                            IBCC0052
      CIRCW=SCIRCW*MS*1.05435E-03                                           IBCC0053
      WIN=MP*CP*(T1-T3)*1.05435E-03                                         IBCC0054
      IH=TG*COMP(ETAC,PFPE,Z)                                               IBCC0055
      EFREC=EFF(II,IH,IC)                                                   IBCC0056
      IF(EFREC.GT. 0.99) GO TO 60                                           IBCC0057
      TD=TC-(TI-IH)                                                         IBCC0058
      TF=TE*COMP(ETAC,PFPE,Z)                                               IBCC0059
      ETAOVL=WOUTM/WIN                                                      IBCC0060
      WRITE(KO,20)                                                          IBCC0061
   20 FORMAT('1',////,T20,'INDIRECT BRAYTON CYCLE STATE POINTS',//,T15,'    IBCC0062
     1POINT',T25,'TEMP(R)',T35,'P(PSIA)',//)                                IBCC0063
      WRITE(KO,25) T1,P1,T2,P2,T3,P3                                        IBCC0064
   25 FORMAT('0',T17,'1',4X,2F10.2,/,T17,'2',4X,2F10.2,/,T17,'3',4X,2F10    IBCC0065
     1.2,/)                                                                 IBCC0066
      WRITE(KO,30) TA,PA,TB,PB,TC,PC,TD,PD,TE,PE,TF,PF,TG,PG,TH,PH,TI,PI    IBCC0067
   30 FORMAT('0',T17,'A',4X,2F10.2,/,T17,'B',4X,2F10.2,/,T17,'C',4X,2F10    IBCC0068
     1.2,/,T17,'D',4X,2F10.2,/,T17,'E',4X,2F10.2,/,T17,'F',4X,2F10.2,/,T    IBCC0069
     217,'G',4X,2F10.2,/,T17,'H',4X,2F10.2,/,T17,'I',4X,2F10.2,//)          IBCC0070
      WRITE(KO,40) EFREC,ETAOVL,PAPB,PFPE                                   IBCC0071
   40 FORMAT('0', T17,'EFREC=',F6.4,//,T17,'ETAOVL=',F6.4,//,T17,'PA/PB=    IBCC0072
```

```
   1',F7.4,//,T17,'PE/PE=',F7.4)                                           IBCC0073
    WRITE(KO,45) WIN,CIRCW,MP,MS,WOUTS,WOUTM                               IBCC0074
45 FORMAT('0',T17,'REACTOR POWER (MW) =',F7.2,//,T17,'CIRCULATOR WORK      IBCC0075
   1 (MW) =',F7.2,//,T17,'PRIMARY FLOW RATE (LBS/SEC) =',F7.2,//,T17,'     IBCC0076
   2SECONDARY FLOW RATE (LBS/SEC) =',F7.2,//,T17,'WORK OUTPUT (SHP) ='     IBCC0077
   3,F10.0,//,T17,'WORK OUTPUT (MW) =',F10.0)                              IBCC0078
    WRITE(KO,46) EFPRI                                                     IBCC0079
46 FORMAT('0',T17,'PRIMARY HX EFFECTIVENESS =',F7.4)                       IBCC0080
60 WRITE(KO,12)                                                            IBCC0081
12 FORMAT('1')                                                             IBCC0082
50 STOP                                                                    IBCC0083
    END                                                                    IBCC0084
```

INDIRECT BRAYTON CYCLE STATE POINTS

POINT	TEMP(F)	P(PSIA)
1	2160.00	1500.00
2	1226.26	1490.00
3	1264.00	1590.00
A	1995.22	1600.00
B	1454.67	650.00
C	1122.86	311.64
D	891.66	301.64
E	560.00	291.64
F	830.28	692.37
G	560.00	682.37
H	830.28	1620.00
I	1061.48	1610.00

EFREC=0.7992

ETAOVL=0.3282

PA/PB= 2.4615

PF/PE= 2.3741

REACTOR POWER (MW) = 524.85

CIRCULATOR WORK (MW) = 22.11

PRIMARY FLOW RATE (LBS/SEC) = 448.04

SECONDARY FLOW RATE (LBS/SEC) = 448.04

WORK OUTPUT (SHP) = 231000.

WORK OUTPUT (MW) = 172.

PRIMARY HX EFFECTIVENESS = 0.8500

FIGURE A.6
Sample Output

Appendix B

HEAT EXCHANGER DESIGN

B.1 Background

The computer code HXSIZE is composed of two separate sections. In the first section the length and overall diameter of the heat exchanger tube bundle is determined. The second section determines the size of the shell, tube headers and end closures that are needed to contain the tube bundle. In addition the second section determines weights of equipment and fluids in the heat exchanger. The output includes both "wet" and "dry" weights.

B.2 Sizing the Heat Transfer Matrix

The method used is an adaptation of a method presented by Rohsenow (R8). It starts with a form of the momentum equation for pressure drop,

$$\Delta P = 4f\left(\frac{L}{D}\right)\rho\frac{V^2}{2}. \qquad \text{(B.1)}$$

The variable f is defined as the friction factor, which for turbulent flow in ducts is given by,

$$f \cong \frac{.0791}{R_{eD}^{\,.25}}, \qquad 2300 < R_{eD} < 20{,}000. \qquad \text{(B.2)}$$

or

$$f \cong \frac{.046}{R_{eD}^{\,.20}}, \qquad R_{eD} > 20{,}000. \qquad \text{(B.3)}$$

Here R_{eD} is defined as the Reynolds number based on the equivalent diameter, where

$$R_{eD} = \frac{D_e \rho V}{\mu}. \qquad \text{(B.4)}$$

The equivalent diameter is defined as

$$D_e = \frac{4\text{x FLOW AREA}}{\text{WETTED PERIMETER}} \; . \qquad \text{(B.5)}$$

For circular tubes, the equivalent diameter equals the tube diameter.

The next step in the development employs the Dittus - Boelter equation, to get an expression for the heat transfer coefficient in terms of fluid properties, flow parameters, and geometry,

$$h = .023 \left(\frac{k}{D_e}\right)\left(\frac{D_e \rho V}{\mu}\right)^{.8}\left(\frac{Cp\,\mu}{k}\right)^{.4} . \qquad \text{(B.6)}$$

The fluid heat transfer coefficient can be solved for if D_e, V, and the fluid properties are known. Often this is not the case in the initial stages of design.

The amount of heat transferred is given by,

$$q = \dot{m}_1 \, Cp_1 \, (T_{1i} - T_{1o}) = \dot{m}_2 \, Cp_2 \, (T_{2o} - T_{2i}), \qquad \text{(B.7)}$$

which is also equal to

$$q = U \, A \, \Delta T_{lm} \; . \qquad \text{(B.8)}$$

Here U is the overall heat transfer coefficient defined for the tube side (U_1) as

$$\frac{1}{U_1} = \frac{1}{h_1} + \frac{D_1}{D_o h_2} + \frac{1}{h_{sc}} \; , \qquad \text{(B.9)}$$

where the h's are given by equation (B.6) and h_{sc} is a scale coefficient. The area, A is the total heat transfer area, and is based on the same surface that U is calculated for, so

$$A_1 = \frac{\pi D_1^{\,2}}{4} \, n \, L \; . \qquad \text{(B.10)}$$

The number of tubes is defined as n, and L is their length.

The third component of equation (B.8) is ΔT_{lm}. For a counterflow, shell and tube heat exchanger it is defined as (refer to Figure A.4),

$$\Delta T_{lm} = \frac{(T_{1i} - T_{2o}) - (T_{1o} - T_{2i})}{\ln \dfrac{(T_{1i} - T_{2o})}{(T_{1o} - T_{2i})}} \quad . \qquad \text{(B.11)}$$

These equations are necessary and sufficient to determine the length, number of tubes, velocities, etc. if the flow rate $\dot{m}$, tube diameters and spacing, pressure drop, temperatures, and fluid properties are given. For this study, the first four of these are known, and the fluid properties can be found, so the heat exchanger can be sized.

B.3 Heat Exchanger Weights

The thickness of a particular component of a heat exchanger must be known before weights can be determined. For this study, and hence in HXSIZE, the pressure acting on the shell and end closures, is assumed to be the maximum pressure in the heat exchanger. The equation used to derive the thickness of the shell is,

$$t_s = \frac{P_D \, D_s}{2\,\sigma} \quad . \qquad \text{(B.12)}$$

Here P_D is the maximum system pressure P, multiplied by a factor of safety F, in this study specified to be 1.5. The yield strength of the material σ, was specified to be 60,000 psi. Although these were specified in the code, it is a simple matter to change either of these values. The

unknown shell diameter D_s was solved for by first determining the area that the shell had to enclose. This area is approximately equal to the sum of the tube area, and shell side flow area,

$$A_s = A_t + A_f \quad . \tag{B.13}$$

The total tube area is

$$A_t = \frac{\pi}{4} D_o^2 n \quad , \tag{B.14}$$

and the total shell side flow area is defined as,

$$A_f = \frac{\pi}{4} D_e D_o n \quad . \tag{B.15}$$

So the shell area is assumed to be

$$A_s = \frac{\pi D_s^2}{4} = \frac{\pi}{4} D_o n (D_e + D_o) \; . \tag{B.15}$$

Now the equivalent diameter D_e can be determined in terms of the outside diameter, for the triangular pitch case as

$$D_e = D_o \left(\frac{2\sqrt{3}}{\pi} \left(\frac{S}{D_o} \right)^2 - 1 \right) \quad . \tag{B.16}$$

Here for simplicity one can define a constant Q to be

$$Q = \frac{2\sqrt{3}}{\pi} \left(\frac{S}{D_o} \right)^2 - 1 \quad , \tag{B.17}$$

where S is the center-to-center tube spacing. Combining equations (B.15), (B.16) and (B.17) and solving for D_s, one obtains

$$D_s = D_o \sqrt{n\ (1+Q)} \quad . \tag{B.18}$$

This expression for D_s is an asymptotic lower limit for the minimum shell diameter in which the given tubes with the triangular pitch can fit. As the number of tubes, n, gets

large the expression for D_s comes very close to the accepted value of minimum shell diameter (F2).

Once D_s is determined t_s can be determined. For this study if the thickness so determined was less than 0.5 inches, the thickness was specified to be 0.5 inches. Since the volume of the shell could now be determined, the weight could also be determined.

The calculation for the spherical end closures is similar to that developed above, except the equation used to determine the thickness t_{eb} is,

$$t_{eb} = \frac{P_D \; D_s}{4 \sigma} \; . \tag{B.19}$$

The end closures were therfore $\frac{1}{2}$ the thickness of the shell. As above, a minimum thickness of 0.25 inches was specified for t_{eb}.

The determination of the tube header sheets is considerably different. Figure B.1 taken from reference (F2) is a plot of dimensionless parameter α , versus the tube diameter/spacing ratio, D_o/S. The parameter α is defined as,

$$\alpha = \frac{\sigma_{MAX} \; t_h^2}{\Delta P \quad r_s^2} \; , \tag{B.20}$$

where σ_{MAX} is the maximum stress in the header, here assumed to be σ , ΔP is the difference between the shell side and tube side pressures, and r_s is the shell radius. Solving for t_h one finds that

$$t_h = r_s \sqrt{\frac{\alpha \quad \Delta P}{\sigma_{MAX}}} \; . \tag{B.21}$$

Figure B.1 includes the effects of densely packed tubes, stress concentrations, and the tube sheet material that must be removed. In HXSIZE α is calculated approximately for any D_o/S ratio.

The remaining weight items are determined by calculating volumes of fluids, and since the densities are known, the weights can be determined. The piping requirements are based on assuming that in the pipes, the fluid velocities are twice the individual velocities in the heat exchanger itself.

B.4 Subroutines

HXSIZE makes use of 3 subroutines to determine property data. These subroutines represent the three fluids of interest in this study. The first subroutine HELIUM, is a modified form of a Helium property subroutine found in WANL-TME-2879 (October 1976). The second is called WATER and consists of a linear interpolation of a table of values of water properties found in Collier (C 3). Finally the last subroutine SWATER uses the same values as WATER, but modifies the density and viscosity for standard salt water (35% salinity).

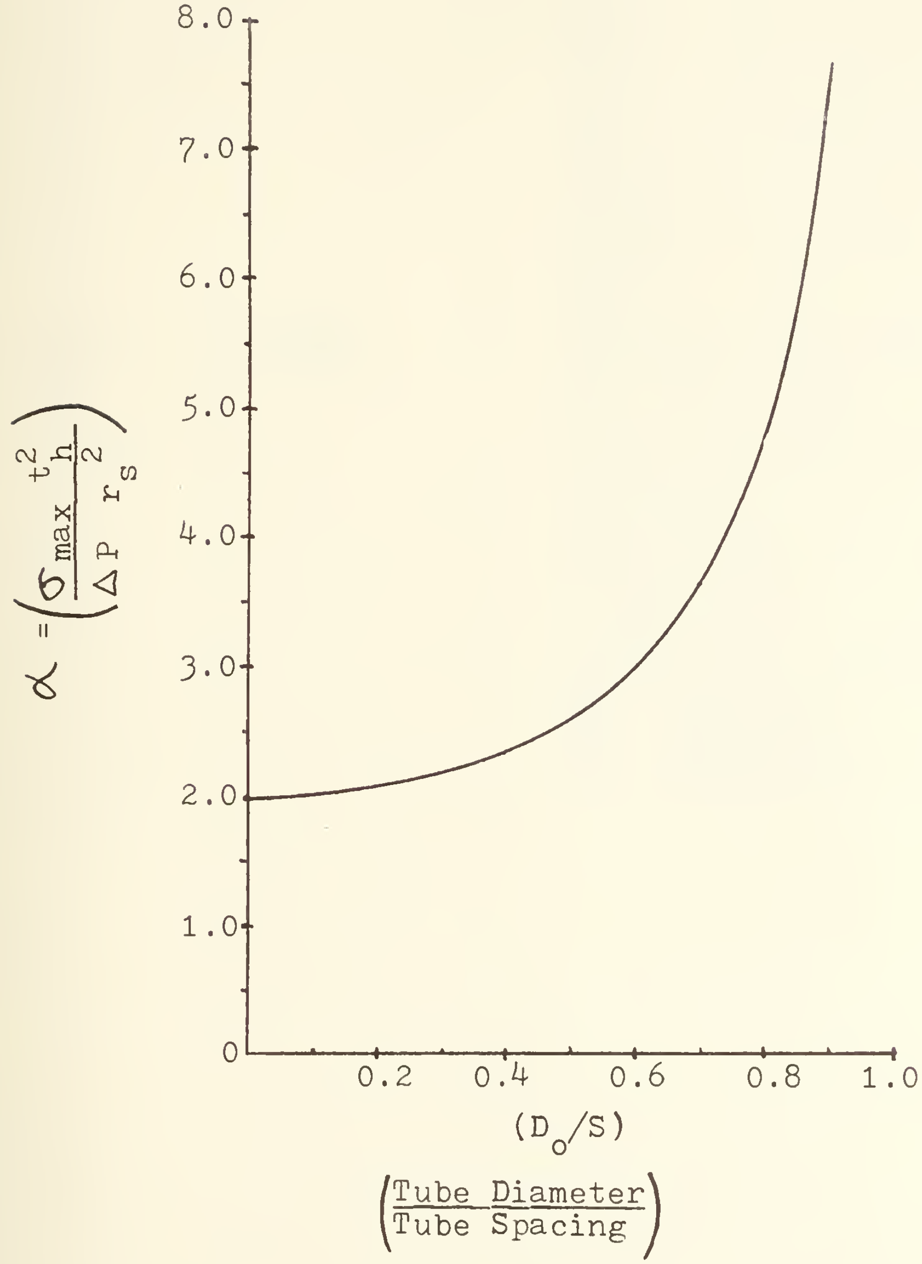
B.5 Input Variables

The following is a list of input variables to HXSIZE, in the order that the computer code accepts them. For input format, consult the code listing in section B.6.

FIGURE B.1

Effect of (D_o/S) on Tube Header Thickness

(Ref. F2 - Table H8.2)



Item		Description
NIN		Number of different heat exchangers to be designed.
THI		"Hot" side inlet temperature (^{o}R).
THO		"Hot" side outlet temperature (^{o}R).
TCI		"Cold" side inlet temperature (^{o}R).
TCO		"Cold" side outlet temperature (^{o}R).
PHI		"Hot" side inlet pressure (PSIA).
PCI		"Cold" side inlet pressure (PSIA).
NU		Number of units/heat exchanger type.
DPH	Specify one only	Pressure drop "hot" side (PSI).
DPC		Pressure drop "cold" side (PSI).
DI		Tube ID (inches).
DO		Tube OD (inches).
PITCH		Center to center tube spacing (inches).
WH		"Hot" fluid flow rate (lbs/sec).
WC		"Cold" fluid flow rate (lbs/sec).
KFC		1 cold fluid in tubes 2 cold fluid in shell
K		Type of heat exchanger K=1 - gas/gas K=2 - gas/water K=3 - water/salt water

```
      ***********************************************
      *                                             *
      *      HEAT EXCHANGER DESIGN CODE             *
      *                                             *
      *                HYSIZE                       *
      *                                             *
      ***********************************************


      COMMON T(20),RHOW(20),CPW(20),VISW(20),TKW(20)
      REAL*4 K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11,K12
      REAL*4 M1,M2
      DATA G,PI,SQR3 / 32.17, 3.141593 , 1.732051 /
      DATA RHOCN, PSC,C / 558.0, .0005, 20000. /
      DATA RHOS,SIG ,F / 499.33, 60000., 1.5 /
      DF=1.2
      DO 400 J=1,20
  400 READ(5,401) T(J),RHOW(J),CPW(J),VISW(J),TKW(J)
  401 FORMAT(3F10.4,2E15.4)
      READ(5,110) NIN
  110 FORMAT(I5)
      DO 50 I=1,NIN
      READ(5,100) THI,THO,TCI,TCO,PHI,PCI
  100 FORMAT(6F10.2)
      READ(5,101) NU,DPH,DPC,DI,DO,PITCH
  101 FORMAT(I10,5F10.4)
      READ(5,102) WH,WC,KFC,K
  102 FORMAT(2F10.4,2I10)
      O=(2.*SQR3/PI*(PITCH/DO)**2-1.)
      DOTS=DO/PITCH
      D1IN=DI
      DOIN=DO
      D1=DI/12.
      DO=DO/12.
      D2=O*DO
      DTH=THI-THO
```

```
      DIC=TCO-TCI                                                       HXS10037
      DTA=THI-TCO                                                       HXS10038
      DTB=THO-TCI                                                       HXS10039
   17 WRITE(6,200) THI,THO,TCI,TCO,PHI,PCI                              HXS10040
  200 FORMAT('1',6F15.4)                                                HXS10041
      WRITE(6,201) NU,DPH,DPC,DI,DOIN,PITCH                             HXS10042
  201 FORMAT(' ',I15,5F15.4)                                            HXS10043
      WRITE(6,202) WH,WC,KFC                                            HXS10044
  202 FORMAT(' ',2F15.4,I15)                                            HXS10045
      IF((DTA-DTB).LT.1.) GO TO 15                                      HXS10046
      DTLM=(DTA-DTB)/(ALOG(DTA/DTB))                                    HXS10047
      GO TO 16                                                          HXS10048
   15 DTLM=DTA                                                          HXS10049
   16 TBARH=(THI+THO)/2.                                                HXS10050
      PBARH=PHI-DPH/2.                                                  HXS10051
      TBARC=(TCI+TCO)/2.                                                HXS10052
      PBARC=PCI-DPC/2.                                                  HXS10053
      GO TO (75,76,77) ,K                                               HXS10054
   75 EFF=DIC/(THI-TCI)                                                 HXS10055
      CALL HELIUM(TBARH,PBARH,RHOH,CPH,VSH,CKH,VIH,PRH)                 HXS10056
    1 CALL HELIUM(TBARC,PBARC,RHOC,CPC,VSC,CKC,VIC,PRC)                 HXS10057
      GO TO 5                                                           HXS10058
   76 EFF=DTH/(THI-TCI)                                                 HXS10059
      CALL WATER(TBARC,RHOC,CPC,VIC,CKC,PRC)                            HXS10060
      CALL HELIUM(TBARH,PBARH,RHOH,CPH,VSH,CKH,VIH,PRH)                 HXS10061
      WC=(EFF*WH*CPH*(THI-TCI))/((TCO-TCI)*CPC)                         HXS10062
      VSC=1.E+20                                                        HXS10063
      GO TO 5                                                           HXS10064
   77 EFF=DTH/(THI-TCI)                                                 HXS10065
      CALL SWATER(TBARC,RHOC,CPC,VIC,CKC,PRC)                           HXS10066
      CALL WATER(TBARH,RHOH,CPH,VIH,CKH,PRH)                            HXS10067
      WC=(EFF*WH*CPH*(THI-TCI))/((TCO-TCI)*CPC)                         HXS10068
      VSC=1.E+20                                                        HXS10069
      VSH=1.E+20                                                        HXS10070
    5 GO TO (10,20),KFC                                                 HXS10071
   10 W1=WC                                                             HXS10072
```

```
      DT1=DTC                                                           HXS10073
      DP1=DPC                                                           HXS10074
      RHO1=RHOC                                                         HXS10075
      CP1=CPC                                                           HXS10076
      VS1=VSC                                                           HXS10077
      CK1=CKC                                                           HXS10078
      VI1=VIC                                                           HXS10079
      PR1=PRC                                                           HXS10080
      W2=WH                                                             HXS10081
      DT2=DTH                                                           HXS10082
      DP2=DPH                                                           HXS10083
      RHO2=RHOH                                                         HXS10084
      CP2=CPH                                                           HXS10085
      VS2=VSH                                                           HXS10086
      CK2=CKH                                                           HXS10087
      VI2=VIH                                                           HXS10088
      PR2=PRH                                                           HXS10089
      GO TO 30                                                          HXS10090
   20 W1=WH                                                             HXS10091
      DT1=DTH                                                           HXS10092
      DP1=DPH                                                           HXS10093
      RHO1=RHOH                                                         HXS10094
      CP1=CPH                                                           HXS10095
      VS1=VSH                                                           HXS10096
      CK1=CKH                                                           HXS10097
      VI1=VIH                                                           HXS10098
      PR1=PRH                                                           HXS10099
      W2=WC                                                             HXS10100
      DT2=DTC                                                           HXS10101
      DP2=DPC                                                           HXS10102
      RHO2=RHOC                                                         HXS10103
      CP2=CPC                                                           HXS10104
      VS2=VSC                                                           HXS10105
      CK2=CKC                                                           HXS10106
      VI2=VIC                                                           HXS10107
      PR2=PRH                                                           HXS10108
```

```
 30 A1=.0791                                                              HXS10109
    B1=.25                                                                HXS10110
    A2=A1                                                                 HXS10111
    B2=B1                                                                 HXS10112
    KK=0                                                                  HXS10113
 34 C1=2.*A1                                                              HXS10114
    C2=2.*A2                                                              HXS10115
    K1=(C1*(VI1**B1))/(G*RHO1)                                            HXS10116
    K2=(C2*(VI2**B2))/(G*RHO2)                                            HXS10117
    K3=(.023*CK1*(PR1**.4))/(VI1**.8)                                     HXS10118
    K4=(.023*CK2*(PR2**.4))/(VI2**.8)                                     HXS10119
 80 W1U=W1/FLOAT(NU)                                                      HXS10120
    W2U=W2/FLOAT(NU)                                                      HXS10121
    G1G2=(W1U/W2U)*D2*DO/(D1**2)                                          HXS10122
    IF(KK.GT.0) GO TO 35                                                  HXS10123
    K5=(K1/K2)*(G1G2**(2.-B1))*((D2/D1)**(1.+B1))                         HXS10124
    GO TO 36                                                              HXS10125
 35 K5=(K1/K2)*(G1**(2.-B1))/(G2**(2.-B2))*(D2**(1.+B2))/(D1**(1.+B1))    HXS10126
 36 IF(DP1.LT. .001)   DP1=K5*DP2                                         HXS10127
    IF(DP2.LT. .001)   DP2=DP1/K5                                         HXS10128
    K7=(K3/K4)*((K2*K5/K1)**(1./3.))*((DO/D1)**.2)*((W1U/W2U)**.2)        HXS10129
    K9=CP1*DT1/(4.*DTLM)                                                  HXS10130
    K8=(1./K3)*(1.+(D1/DO)*K7)*DF                                         HXS10131
    G10=0.0                                                               HXS10132
    GO TO 27                                                              HXS10133
271 K8=((1./K3)*(1.+(D1/DO)*K7)+RSC*(G1**.8)/D1**2)*DF                    HXS10134
 27 GIP=((DP1*144.)*D1**(B1-.2))/(K1*K8*K9)                               HXS10135
    K10=GIP**(1./(2.2-B1))                                                HXS10136
    G1=K10                                                                HXS10137
 40 KK=KK+1                                                               HXS10138
    RE1=D1*G1/VI1                                                         HXS10139
    G2=G1/G1G2                                                            HXS10140
    RE2=D2*G2/VI2                                                         HXS10141
    IF(RE1.LT. C) GO TO 41                                                HXS10142
    A1=.046                                                               HXS10143
    B1=.20                                                                HXS10144
```

```
41   IF(B2.LT. C) GO TO 51                                     HXS10145
     A2=.04-                                                   HXS10146
     B2=.20                                                    HXS10147
51   IF(KK.GT. 1)   GO TO 61                                   HXS10148
     IF((RE1.GT.C).OR.(RE2.GT.C))   GO TO 34                   HXS10149
61   GO TO (272,272,273), K                                    HXS10150
273  IF(((G1-G10)/G1).LT. .01) GO TO 272                       HXS10151
     G10=G1                                                    HXS10152
     GO TO 271                                                 HXS10153
272  AI=K9*K8*(D1**1.2)*(G1**.2)                               HXS10154
     K11=(W1U*4.)/(K10*PI)                                     HXS10155
     AN=K11/(D1**2)                                            HXS10156
81   N=IFIX(AN)                                                HXS10157
     K12=PI*K8*K9*(K10**.2)*K11                                HXS10158
     A=K12*(D1**.2)                                            HXS10159
     U1=((G1**.8)/(K8*D1**.2))*3600.                           HXS10160
     D=DO*SORT(AN*(1.+C))                                      HXS10161
     VOI=(AL*PI*(D**2)/4.)*FLOAT(NU)                           HXS10162
     HEAT=U1*A*DTLM*FLOAT(NU)*1.05435E-03/3600.                HXS10163
     V1=G1/RHO1                                                HXS10164
     M1=V1/VS1                                                 HXS10165
     V2=(G1/G1G2)/RHO2                                         HXS10166
     M2=V2/VS2                                                 HXS10167
     PD=F*PHI                                                  HXS10168
     IF(KFC.EQ.2) PD=F*PCI                                     HXS10169
112  TSH=(PD*D)/(2.*SIG)                                       HXS10170
     IF(TSH*12. .LT. .50)   TSH=.50/12.                        HXS10171
     Y=10.*DOTS+1.                                             HXS10172
     X=13.*(1.-(Y/10.)**2.8)*(1./2.3)                          HXS10173
     W=-.5*X+8.5                                               HXS10174
     P=ABS(PHI-PCI)                                            HXS10175
     IF(P.LT.5.) P=PHI                                         HXS10176
     TTS=SQRT(W*P*D**2/(4.*SIG))                               HXS10177
     WTS=RHOS*PI*FLOAT(NU)*TTS*(D**2-AN*DO**2)/2.              HXS10178
     ALI=AL+2.*TTS                                             HXS10179
     WGHT=(DO**2-D1**2)*PI/4.*ALI*FLOAT(N*NU)*RHOS             HXS10180
```

```
      WSHELL=RHOS*PI*ALI*D*TSH*FLOAT(NU)                                HXS10181
      TFB=(PD*D)/(4.*SIG)                                               HXS10182
      IF(TFB*12. .LT. .25)  TFB=.25/12.                                 HXS10183
      WFB=(RHOS*PI*((D**2)*TFB*(1.+2.*TFB/D))/2.)*FLOAT(NU)             HXS10184
      ALOA=ALI+D+2.*TFB                                                 HXS10185
      TT=(DC-D1)*6.                                                     HXS10186
      TSH=TSH*12.                                                       HXS10187
      TTS=TTS*12.                                                       HXS10188
      TFB=TFB*12.                                                       HXS10189
      SWGHT=WGHT+WSHELL+WTS+WFB                                         HXS10190
      TWGHT=SWGHT/2240.                                                 HXS10191
      DODI=DO/D1                                                        HXS10192
      GO TO (501,503,505), K                                            HXS10193
  501 WRITE(6,502)                                                      HXS10194
  502 FORMAT('0',T15,' RECUPERATOR')                                    HXS10195
      GO TO 507                                                         HXS10196
  503 WRITE(6,504)                                                      HXS10197
  504 FORMAT('0',T15,' FRESH WATER COOLER')                             HXS10198
      GO TO 507                                                         HXS10199
  505 WRITE(6,506)                                                      HXS10200
  506 FORMAT('0',T15,' SALT WATER COOLER')                              HXS10201
  507 WRITE(6,207) EFF,HEAT                                             HXS10202
  207 FORMAT('+',T40,'EFFECTIVENESS =',F6.3,10X,'HEAT LOAD (MW) =',F7.2,HXS10203
     1/,T5,' HX MATRIX PARAMETERS')                                     HXS10204
  508 WRITE(6,203) NU,N,A,AL,RE1,RE2,D,VOL                              HXS10205
  203 FORMAT(' ', /,T5,' NUMBER OF UNITS = ',I5, /,T5,' NO. TUBES/UNIT =HXS10206
     1', I9, /,T5,' H.T. AREA/UNIT =', F9.2, /,T5,' LENGTH =',F17.2, /, HXS10207
     2T5,' TUBE NRE =',F15.0, /,T5,' SHELL NRE =',F14.0, /,T5,' SHELL DIHXS10208
     3AMETER =', F9.3, /,T5,' VOLUME =',F17.2)                          HXS10209
      WRITE(6,204) U1,DTLM,V1,M1,V2,M2                                  HXS10210
  204 FORMAT(' ',T5,' OVERALL U1 =',F13.1, /,I6,'DEL T(LM) =',F14.2,/,T5HXS10211
     1,' TUBE VELOCITY =',F10.2, /,T5,' TUBE MACH NO. =',F10.4, /,T5,' SHXS10212
     2HELL VELOCITY =', F9.2, /,T5,' SHELL MACH NO. =',F9.4)            HXS10213
      WRITE(6,205) PD,F,SIG,D1IN,DOIN,LODI                              HXS10214
  205 FORMAT('0',T20,' HEAT EXCHANGER DESIGN',/,T5,' DESIGN PRESSURE =',HXS10215
     1F8.1,5X,' SAFETY FACTOR =',F4.1,5X,' YIELD STRESS =',F8.0,/,T5,' THXS10216
```

```
     2UBE ID. =',F6.3,' IN.',5X,' TUBE OD. =',F6.3,' IN.',5X,' DO/DI =',   HXS10217
     3F7.4,/,T29,'(LBS)',T50,'(IN)')                                       HXS10218
      WRITE(6,205) WGHT,TT,WSHELL,TSH,WTS,TTS,WEB,TEB,SWGHT,TWGHT,ALOA     HXS10219
  205 FORMAT(' ',T5,' CORE',15X,F10.0,10X,F10.4,/,T5,' SHELL',14X,F10.0,   HXS10220
     11CX,F10.4,/,T5,' TUBE SHEETS',8X,F10.0,10X,F10.4,/,T5,' END CLOSUR   HXS10221
     2ES',7X,F10.0,10X,F10.4,//,T6,'EQUIPMENT WEIGHT',F14.0,' (LBS)',4X,   HXS10222
     3F10.2,' (TONS)',10X,'TOTAL LENGTH (FT) =',F5.2)                      HXS10223
      GO TO (70,71), KFC                                                   HXS10224
   70 DPC=DP1                                                              HXS10225
      DPH=DP2                                                              HXS10226
      GO TO 72                                                             HXS10227
   71 DPC=DP2                                                              HXS10228
      DPH=DP1                                                              HXS10229
   72 WRITE(6,162) TCO,DPH,DPC                                             HXS10230
  162 FORMAT('0',T5,' COOLANT DISCH. TEMP. (F) =',F6.1,10X,' PRESSURE DR   HXS10231
     1OP (H) =',F6.3,10X,' PRESSURE DROP (C) =',F6.3)                      HXS10232
  150 GO TO (151,152), KFC                                                 HXS10233
  151 WP=(PI*(D1**2)/4.)*V1*DPC*144.*FLOAT(N*NU)/550.                      HXS10234
      GO TO 160                                                            HXS10235
  152 WP=(PI*(DO*D2)/4.)*V2*DPC*144.*FLOAT(N*NU)/550.                      HXS10236
  160 WRITE(6,161) WH,WC,WP                                                HXS10237
  161 FORMAT('0',T4,'  PRIMARY FLOW RATE =',F7.1,10X,' COOLANT FLOW RATE   HXS10238
     1 =',F7.1,10X,' COOLANT PUMPING POWER (HP) =',F10.0)                  HXS10239
      IF(K.EQ.3)  GO TO 900                                                HXS10240
      RHOM=RHOS                                                            HXS10241
      GO TO 901                                                            HXS10242
  900 RHOM=RHCON                                                           HXS10243
  901 G2=G1/G1G2                                                           HXS10244
      DPTS=SQRT((2.*W1U)/(PI*G1))                                          HXS10245
      TPTS=(PD*DPTS)/(2.*SIG)                                              HXS10246
      IF(TPTS*12. .LT. .5) TPTS=.5/12.                                     HXS10247
      WPTS=PI*DPTS*TPTS*RHOM                                               HXS10248
      DPSS=SQRT((2.*W2U)/(PI*G2))                                          HXS10249
      TPSS=(PD*DPSS)/(2.*SIG)                                              HXS10250
      IF(TPSS*12. .LT. .5) TPSS=.5/12.                                     HXS10251
      WPSS=PI*DPSS*TPSS*RHOM                                               HXS10252
```

```
      F1=ALI*RHO1*AN*FLOAT(NU)
      WATT=(F1*PI*D1**2)/4.
      WATH=(FLOAT(NU)*PI*RHO1*D**3)/3.
      WIPIS=(PI*RHO1*DPIS**2)/4.
      F2=(RHO2/RHO1)*F1
      WATSH=(F2*PI*OYDC**2)/4.
      WIPSS=(PI*RHO2*DPSS**2)/4.
      TPISIN=TPIS*12.
      TPSSIN=TPSS*12.
      WRITE(6,600) DPIS,TPISIN,WPIS,WIPIS,DPSS,TPSSIN,WPSS,WIPSS
  600 FORMAT(' ',T22,' PIPING REQUIREMENTS',/,T22,' DIA (FT)',T35,'T (IN
     1)',T46,'PIPE (LBS/FT)',10X,'FLUID (LBS/FT)',/,T6,'TUBE SIDE',F14.3
     2,F11.3,F17.1,F24.1,/,T5,' SHELL SIDE',F13.3,F11.3,F17.1,F24.1)
      WRITE(6,601) WATT,WATSH,WATH
  601 FORMAT('0',T21,'FLUID WEIGHTS'//,T5,' WEIGHT IN TUBES',F11.2,' (LB
     1S)',/,T5,' WEIGHT IN SHELL',F11.2,' (LBS)',/,T5,' WEIGHT IN HEADER
     2',F10.2,' (LBS)')
      WFINHX=WATT+WATSH+WATH
      WEIGHT=SWGHT+WFINHX
      TWGHT=WEIGHT/2240.
      TFINHX=WFINHX/2240.
      TSWGHT=SWGHT/2240.
      WRITE(6,602)
  602 FORMAT('0',T23,'TOTAL SYSTEM WEIGHT',/,T22,'(LBS)', 8X,'(TONS)',/)
      WRITE(6,603) WFINHX,TFINHX,SWGHT,TSWGHT,WEIGHT,TWGHT
  603 FORMAT(' ',T5,' FLUID IN HX',F12.2,F10.1,/,T5,' EQUIPMENT',F14.2,F
     110.1,//,T5,' TOTAL',F18.2,F10.1)
   50 CONTINUE
      WRITE(6,999)
  999 FORMAT('1')
      STOP
      END
```

```
      *****************************************
      *                                       *
      *      HELIUM PROPERTIES SUBROUTINE     *
      *                                       *
      *          (REF. WANL TME-2879)         *
      *                                       *
      *             OCTOBER 1976              *
      *                                       *
      *****************************************

      SUBROUTINE HELIUM(T,P,RHO,CP,VS,CK,VI,PR)
      DATA A,B,R,D / .06310, .0005342,  2.68111, 1.4234E-07 /
      DATA SFT,CF,GC,C1 / 144., .18508, -32.1667, 2.5182E-05 /
      DATA CPO / 1.2413 /
      KKK=1
      IF(T.LT.450.) GO TO 32
      IF(T.GT.3000.) GO TO 32
      IF(P.LT. .1) GO TO 31
      IF(P.GT.3000.) GO TO 32
      GO TO 33
   31 P=.1
   32 IF(KKK.GT.20) GO TO 33
      KKK=KKK+1
      WRITE(6,101) T,P
  101 FORMAT(26H0IND. VAR. OUT OF RANGE T=,F12.4,3H P=,F12.4)
   33 SRT=SQRT(T)
      RTP=R*T/P
      BT=B*SRT
      BOT=B/SRT/2.
      V=RTP+A-BT
      CP=CPO-(.5*BOT*P*CF)
      DVDP=-RTP/P
      CV=CP+T*(((R/P-BOT)**2.)*CF)/DVDP
      VS=V*SQRT(GC*CP/(CV*DVDP/SFT))
      VI=D*T**.719215/(1.-5288./T**2)
```

```
CK=6696.*VI+.00336/V                HXS20037
CK=CK/3600.                         HXS20038
EA=CP*VI/CK                         HXS20039
RHO=1./V                            HXS20040
RETURN                              HXS20041
END                                 HXS20042
```

```
      ************************************        HXS30001
      *                                  *        HXS30002
      *     WATER PROPERTIES SUBROUTINE  *        HXS30003
      *                                  *        HXS30004
      ************************************        HXS30005
                                                  HXS30006
                                                  HXS30007
      SUBROUTINE WATER(TB,RHO,CP,VI,CK,PR)        HXS30008
      COMMON T(20),RHOW(20),CPW(20),VISW(20),TKW(20)  HXS30009
      FIT(A,B,C)=A+(B-A)*C                        HXS30010
      DO 1 I=1,20                                 HXS30011
      IF(TB-T(I)) 2,2,1                           HXS30012
    1 CONTINUE                                    HXS30013
    2 X=(TB-T(I-1))/(T(I)-T(I-1))                 HXS30014
      CP=FIT(CPW(I-1),CPW(I),X)                   HXS30015
      RHO=FIT(RHOW(I-1),RHOW(I),X)                HXS30016
      VI=FIT(VISW(I-1),VISW(I),X)                 HXS30017
      CK=FIT(TKW(I-1),TKW(I),X)                   HXS30018
      PR=CP*VI/CK                                 HXS30019
      RETURN                                      HXS30020
      END                                         HXS30021
```

```
********************************************    HXS40001
*                                          *    HXS40002
*        WATER PROPERTIES DATA             *    HXS40003
*                                          *    HXS40004
*    (REF. COLLIER(C3)   TABLE A.3         *    HXS40005
*                                          *    HXS40006
********************************************    HXS40007
                                                HXS40008
                                                HXS40009
 1ST COLUMN - TEMPERATURE (RANKINE)             HXS40010
 2ND COLUMN - DENSITY (LBS/FT**3)               HXS40011
 3RD COLUMN - SPECIFIC HEAT (BTU/LB - F)        HXS40012
 4TH COLUMN - VISCOSITY (LB/SEC-FT)             HXS40013
 5TH COLUMN - THERMAL CONDUCTIVITY (BTU/SEC-FT-F)  HXS40014
                                                HXS40015
                                                HXS40016
510.   62.4    1.0015   5.763E-04   9.42E-05    HXS40017
528.   62.32   0.999    6.733E-04   9.68E-05    HXS40018
546.   62.16   0.998    5.365E-04   9.92E-05    HXS40019
564.   61.94   0.998    4.394E-04   1.01E-04    HXS40020
582.   61.68   0.998    3.681E-04   1.03E-04    HXS40021
600.   61.38   0.999    3.140E-04   1.05E-04    HXS40022
618.   61.04   1.001    2.720E-04   1.06E-04    HXS40023
636.   60.67   1.002    2.388E-04   1.08E-04    HXS40024
654.   60.27   1.005    2.121E-04   1.08E-04    HXS40025
672.   59.83   1.007    1.902E-04   1.09E-04    HXS40026
690.   59.37   1.010    1.712E-04   1.10E-04    HXS40027
708.   58.88   1.013    1.552E-04   1.10E-04    HXS40028
726.   58.36   1.018    1.417E-04   1.10E-04    HXS40029
744.   57.82   1.023    1.304E-04   1.10E-04    HXS40030
762.   57.24   1.028    1.208E-04   1.10E-04    HXS40031
780.   56.66   1.035    1.127E-04   1.10E-04    HXS40032
798.   56.02   1.043    1.058E-04   1.09E-04    HXS40033
816.   55.37   1.051    9.979E-05   1.09E-04    HXS40034
834.   54.69   1.062    9.455E-05   1.08E-04    HXS40035
852.   53.98   1.073    8.998E-05   1.07E-04    HXS40036
```

```
      ***************************************************           HXS50001
      *                                                 *           HXS50002
      *      SALT WATER PROPERTIES SUBROUTINE           *           HXS50003
      *                                                 *           HXS50004
      ***************************************************           HXS50005
                                                                    HXS50006
                                                                    HXS50007
      SUBROUTINE SWATER(TB,RHO,CP,VI,CK,PR)                         HXS50008
      COMMON T(20),RHOW(20),CPW(20),VISW(20),TKW(20)                HXS50009
      FIT(A,B,C)=A+(B-A)*C                                          HXS50010
      DO 1 I=1,20                                                   HXS50011
      IF(TB-T(I)) 2,2,1                                             HXS50012
    1 CONTINUE                                                      HXS50013
    2 X=(TB-T(I-1))/(T(I)-T(I-1))                                   HXS50014
      CP=FIT(CPW(I-1),CPW(I),X)                                     HXS50015
      RHO=FIT(RHOW(I-1),RHOW(I),X)*(1.028307-(2.46E-05*(TB-460.)))  HXS50016
      VI=FIT(VISW(I-1),VISW(I),X)*(0.9775524*(TB-460.)**(0.0424963))HXS50017
      CK=FIT(TKW(I-1),TKW(I),X)                                     HXS50018
      PR=CP*VI/CK                                                   HXS50019
      RETURN                                                        HXS50020
      END                                                           HXS50021
```

B.7 Output Description

All output variables have the dimensions indicated; where none is indicated, length dimensions are all in feet (i.e. Volume - ft^3), temperatures are in degrees Rankine, velocities are in feet per second. The overall heat transfer coefficient on the tube side U_1 has the units (BTU/hr-ft^2-^oR).

Figures B.2 through B.6 are output listings for the heat exchangers used in the modified plant (0.25 inch OD tubes). Figures B.7 through B.11 are the ouput listings as B.2-B.7, with only the tube diameters and spacings changed (basically 0.12 inch OD tubes). The numbers found immediately at the top of each listing are the input variables, in the same order and with the same dimensions as listed in section B.5.

FIGURE B.2

Primary Heat Exchanger-0.25 in. OD tubes

```
2160.0000      1226.2600      1061.4790      1995.2190      1500.0000      1610.0000
        4         5.0000         0.0000         0.2140         0.2500         0.3375
 448.0400       448.0400              2

        RECUPERATOR               EFFECTIVENESS = 0.850          HEAT LOAD (MW) = 547.13
HX MATRIX PARAMETERS

NUMBER OF UNITS =        4
NO. TUBES/UNIT =     13031
H.T. AREA/UNIT = 15311.95
LENGTH =             15.16
TUBE NRE =          14914.
SHELL NRE =         13644.
SHELL DIAMETER =     3.966
VOLUME =            748.90
OVERALL U1 =         185.1
DEL T(LM) =         164.78
TUBE VELOCITY =      76.41
TUBE MACH NO. =     0.0128
SHELL VELOCITY =     46.70
SHELL MACH NO. =    0.0082

              HEAT EXCHANGER DESIGN
DESIGN PRESSURE =  2415.0      SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.214 IN.      TUBE OD. = 0.250 IN.      DO/DI = 1.1682
                         (LBS)                (IN)
CORE                    51269.               0.0180
SHELL                   31033.               0.9577
TUBE SHEETS              5805.               2.8099
END CLOSURES             2009.               0.4789

EQUIPMENT WEIGHT         90115.  (LBS)        40.23 (TONS)         TOTAL LENGTH (FT) =19.67

COOLANT DISCH. TEMP. (F) =1995.2          PRESSURE DROP (H) = 5.000          PRESSURE DROP (C) = 1.920

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE =  448.0          COOLANT PUMPING POWER (HP) =       583.
                PIPING REQUIREMENTS
                DIA (FT)    T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE        1.693      0.500          110.7                    0.7
SHELL SIDE       1.988      0.500          129.9                    1.2

               FLUID WEIGHTS

WEIGHT IN TUBES       91.62  (LBS)
WEIGHT IN SHELL      149.91  (LBS)
WEIGHT IN HEADER      85.03  (LBS)

                 TOTAL SYSTEM WEIGHT
                (LBS)         (TONS)

FLUID IN HX       326.56         0.1
EQUIPMENT       90115.06        40.2

TOTAL           90441.56        40.4
```

FIGURE B.3

Recuperator-0.25 in. OD tubes

```
 1122.8600       891.6599       830.2800      1061.4790       311.6399      1620.0000
         2         5.0000        0.0000         0.2140         0.2500         0.3375
  448.0400       449.0400             2

      RECUPERATOR             EFFECTIVENESS = 0.790          HEAT LOAD (MW) = 135.54
HX MATRIX PARAMETERS

NUMBER OF UNITS =       2
NO. TUBES/UNIT =    49461
H.T. AREA/UNIT = 28021.92
LENGTH =            10.11
TUBE NPE =         15638.
SHELL NPE =        13906.
SHELL DIAMETER =    6.568
VOLUME =           685.27
OVERALL U1 =        134.5
DEL T(LM) =         61.38
TUBE VELOCITY =    159.24
TUBE MACH NO. =    0.0347
SHELL VELOCITY =    21.22
SHELL MACH NO. =   0.0047

           HEAT EXCHANGER DESIGN
DESIGN PRESSURE =  2430.0     SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.214 IN.      TUBE OD. = 0.250 IN.      DO/DI = 1.1682
                        (LBS)              (IN)
CORE                    57545.             0.0180
SHELL                   35048.             1.5961
TUBE SHEETS             45476.            16.0505
END CLOSURES             4592.             0.7980

EQUIPMENT WEIGHT        142660.  (LBS)       63.69 (TONS)          TOTAL LENGTH (FT) =19.49

COOLANT DISCH. TEMP. (F) =1061.5          PRESSURE DROP (H) = 5.000          PRESSURE DROP (C) = 0.421

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE =  448.0          COOLANT PUMPING POWER (HP) =        80.
            PIPING REQUIREMENTS
            DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE    2.804       0.681          242.8                    0.7
SHELL SIDE   3.292       0.800          344.2                    5.3

           FLUID WEIGHTS

WEIGHT IN TUBES       35.98 (LBS)
WEIGHT IN SHELL      270.05 (LBS)
WEIGHT IN HEADER      67.58 (LBS)

            TOTAL SYSTEM WEIGHT
           (LBS)         (TONS)

FLUID IN HX       373.60        0.2
EQUIPMENT      142660.20       63.7

TOTAL          143033.80       63.9
```

FIGURE B.4

Precooler-0.25 in. OD tubes

```
   891.6599         560.0000         555.0000         608.0000         301.6399          70.0000
          4           8.0000           0.0000           0.2140           0.2500           0.3083
   448.0400           0.0000                1

        FRESH WATER COOLER      EFFECTIVENESS = 0.985          HEAT LOAD (MW) = 194.43
HX MATRIX PARAMETERS

NUMBER OF UNITS =       4
NO. TUBES/UNIT =    16807
H.T. AREA/UNIT =  7106.14
LENGTH =             7.55
TUBE NRE =         10004.
SHELL NRE =        24910.
SHELL DIAMETER =    3.498
VOLUME =           290.02
OVERALL U1 =        338.5
DEL T(LM) =         69.00
TUBE VELOCITY =      3.37
TUBE MACH NO. =    0.0000
SHELL VELOCITY =   190.24
SHELL MACH NO. =   0.0488

             HEAT EXCHANGER DESIGN
DESIGN PRESSURE =   452.5      SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.214 IN.      TUBE OD. = 0.250 IN.      DO/DI = 1.1682
                       (LBS)              (IN)
CORE                  24955.             0.0180
SHELL                  7462.             0.5000
TUBE SHEETS            4751.             3.6802
END CLOSURES            809.             0.2500

EQUIPMENT WEIGHT        37977.  (LBS)         16.95 (TONS)          TOTAL LENGTH (FT) =11.70

COOLANT DISCH. TEMP. (F) = 606.0           PRESSURE DROP (H) = 8.000          PRESSURE DROP (C) = 1.010

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE = 3486.5          COOLANT PUMPING POWER (HP) =       15.
                PIPING REQUIREMENTS
                DIA (FT)     T (IN)     PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE        1.635       0.500          106.9                  129.5
SHELL SIDE       1.571       0.500          102.7                    0.3

             FLUID WEIGHTS

WEIGHT IN TUBES     8452.78 (LBS)
WEIGHT IN SHELL       19.22 (LBS)
WEIGHT IN HEADER   11055.88 (LBS)

                TOTAL SYSTEM WEIGHT
               (LBS)          (TONS)

FLUID IN HX     19527.87        8.7
EQUIPMENT       37977.26       17.0

TOTAL           57505.13       25.7
```

FIGURE B.5

Intercooler-0.25 in. OD tubes

```
830.2800        560.0000       555.0000       608.0000       692.3701       70.0000
       4          4.0000         0.0000         0.2140         0.2500        0.3093
448.0400          0.0000              1

        FRESH WATER COOLER     EFFECTIVENESS = 0.982       HEAT LOAD (MW) = 158.40
HX MATRIX PARAMETERS

NUMBER OF UNITS =        4
NO. TUBES/UNIT =     15576
H.T. AREA/UNIT =   6953.46
LENGTH =              7.97
TUBE NPE =           9795.
SHELL NPE =         27591.
SHELL DIAMETER =     3.367
VOLUME =            284.03
OVERALL U1 =         339.3
DEL T(LM) =          57.26
TUBE VELOCITY =       2.96
TUBE MACH NO. =     0.1000
SHELL VELOCITY =     85.66
SHELL MACH NO. =    0.0222

             HEAT EXCHANGER DESIGN
DESIGN PRESSURE =  1038.6     SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.214 IN.      TUBE OD. = 0.250 IN.      DO/DI = 1.1682
                         (LBS)              (IN)
CORE                    25347.            0.0180
SHELL                    7872.            0.5000
TUBE SHEETS              6948.            5.8073
END CLOSURES              750.            0.2500

EQUIPMENT WEIGHT        40917. (LBS)        18.27 (TONS)         TOTAL LENGTH (FT) =12.35

COOLANT DISCH. TEMP. (R) = 608.0         PRESSURE DROP (H) = 4.000         PRESSURE DROP (C) = 0.852

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE = 2840.4          COOLANT PUMPING POWER (HP) =        10.
               PIPING REQUIREMENTS
               DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE       1.574       0.500          102.9                   120.0
SHELL SIDE      1.513       0.500           98.9                     0.7

             FLUID WEIGHTS

WEIGHT IN TUBES    8585.21 (LBS)
WEIGHT IN SHELL      46.78 (LBS)
WEIGHT IN HEADER   9863.48 (LBS)

               TOTAL SYSTEM WEIGHT
               (LBS)          (TONS)

FLUID IN HX    18495.47         8.3
EQUIPMENT      40917.34        18.3

TOTAL          59412.81        26.5
```

FIGURE B.6

Salt Water Cooler-0.3375 in. OD tubes

```
  608.0000        555.0000        545.0000        576.0000        70.0000        70.0000
         2          0.0000         20.0000          0.2770         0.3750         0.5063
 6325.3330          0.0000               1

            SALT WATER COOLER         EFFECTIVENESS = 0.841          HEAT LOAD (MW) = 352.84
HX MATRIX PARAMETERS

NUMBER OF UNITS =      2
NO. TUBES/UNIT =     21133
H.T. AREA/UNIT = 47556.63
LENGTH =            30.96
TUBE NPS =        26737.
SHELL NPS =       16441.
SHELL DIAMETER =    6.448
VOLUME =          2021.93
OVERALL U1 =       669.7
DEL T(LM) =        18.91
TUBE VELOCITY =     9.59
TUBE MACH NO. =   0.0000
SHELL VELOCITY =    3.13
SHELL MACH NO. =  0.0000

               HEAT EXCHANGER DESIGN
DESIGN PRESSURE =   105.0       SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.277 IN.      TUBE OD. = 0.375 IN.      DO/DI = 1.3538
                        (LBS)               (IN)
CORE                   232708.              0.0490
SHELL                   26608.              0.5000
TUBE SHEETS              9955.              3.6447
END CLOSURES             1368.              0.2500

EQUIPMENT WEIGHT       270638. (LBS)       120.82 (TONS)          TOTAL LENGTH (FT) =38.05

COOLANT DISCH. TEMP. (R) = 576.0         PRESSURE DROP (H) = 1.732          PRESSURE DROP (C) =20.000

PRIMARY FLOW RATE = 6326.9          COOLANT FLOW RATE =10816.9          COOLANT PUMPING POWER (HP) =      891.
                  PIPING REQUIREMENTS
                  DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE          2.376       0.500           173.5                  281.8
SHELL SIDE         3.232       0.500           236.1                  506.1

               FLUID WEIGHTS

WEIGHT IN TUBES    35534.98 (LBS)
WEIGHT IN SHELL    63904.77 (LBS)
WEIGHT IN HEADER   35706.14 (LBS)

                  TOTAL SYSTEM WEIGHT
                 (LBS)          (TONS)

FLUID IN HX    135195.30         60.4
EQUIPMENT      270637.50        120.8

TOTAL          405833.40        181.2
```

FIGURE B.7

Primary Heat Exchanger-0.12 in. OD tubes

```
 2160.0000      1226.2600      1061.4790      1995.2190      1500.0000      1610.0000
         4         5.0000         0.0000         0.1000         0.1200         0.1620
  448.0400       448.0400              2

        RECUPERATOR              EFFECTIVENESS = 0.850          HEAT LOAD (MW) = 547.13
HX MATRIX PARAMETERS

NUMBER OF UNITS =        4
NO. TUBES/UNIT =     84692
H.T. AREA/UNIT =  13572.52
LENGTH =              6.12
TUBE NRE =           6749.
SHELL NRE =          6052.
SHELL DIAMETER =     4.125
VOLUME =            327.30
OVERALL U1 =         208.8
DEL T(LM) =         164.76
TUBE VELOCITY =      74.50
TUBE MACH NO. =     0.0124
SHELL VELOCITY =     43.16
SHELL MACH NO. =    0.0076

              HEAT EXCHANGER DESIGN
DESIGN PRESSURE =  2415.0      SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.100 IN.      TUBE OD. = 0.120 IN.      DO/DI = 1.2000
                    (LBS)              (IN)
CORE                26827.             0.0100
SHELL               14203.             0.9963
TUBE SHEETS          6535.             2.9231
END CLOSURES         2261.             0.4982

EQUIPMENT WEIGHT        49827. (LBS)        22.24 (TONS)        TOTAL LENGTH (FT) =10.82

COOLANT DISCH. TEMP. (R) =1995.2         PRESSURE DROP (H) = 5.000          PRESSURE DROP (C) = 1.690

PRIMARY FLOW RATE =  448.0         COOLANT FLOW RATE =  448.0         COOLANT PUMPING POWER (HP) =     513.
                PIPING REQUIREMENTS
                DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE        1.715       0.500           112.1                   0.8
SHELL SIDE       2.068       0.500           135.1                   1.3

              FLUID WEIGHTS

WEIGHT IN TUBES      39.74 (LBS)
WEIGHT IN SHELL      68.61 (LBS)
WEIGHT IN HEADER     95.73 (LBS)

              TOTAL SYSTEM WEIGHT
              (LBS)        (TONS)

FLUID IN HX       204.08        0.1
EQUIPMENT       49826.55       22.2

TOTAL           50030.63       22.3
```

FIGURE B.8

Recuperator-0.12 in. OD tubes

```
1122.9600       891.6599        830.2800        1061.4790       311.6399        1620.0000
        2         5.0000          0.0000           0.1000         0.1200           0.1620
 448.0400       448.0400               2

        RECUPERATOR             EFFECTIVENESS = 0.790           HEAT LOAD (MW) = 135.54
HX MATRIX PARAMETERS

NUMBER OF UNITS =        2
NO. TUBES/UNIT =    232312
H.T. AREA/UNIT = 24835.51
LENGTH =              4.08
TUBE NRE =           7125.
SHELL NRE =          6208.
SHELL DIAMETER =     6.833
VOLUME =            299.46
OVERALL U1 =         151.8
DEL T(LM) =          61.38
TUBE VELOCITY =     155.27
TUBE MACH NO. =     0.0339
SHELL VELOCITY =     13.61
SHELL MACH NO. =    0.0043

                HEAT EXCHANGER DESIGN
DESIGN PRESSURE =  2430.0       SAFETY FACTOR = 1.5       YIELD STRESS =  60000.
TUBE ID. = 0.100 IN.       TUBE OD. = 0.120 IN.       DO/DI = 1.2000
                          (LBS)                (IN)
CORE                      38229.               0.0100
SHELL                     20365.               1.6603
TUBE SHEETS               51192.              16.6967
END CLOSURES               5169.               0.8302

EQUIPMENT WEIGHT        114955. (LBS)       51.32 (TONS)         TOTAL LENGTH (FT) =13.84

COOLANT DISCH. TEMP. (R) =1061.5          PRESSURE DROP (H) = 5.000          PRESSURE DROP (C) = 0.371

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE =  448.0          COOLANT PUMPING POWER (HP) =       70.
                PIPING REQUIREMENTS
                DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE        2.840       0.690          256.2                   0.7
SHELL SIDE       3.424       0.832          372.5                   5.7

                FLUID WEIGHTS

WEIGHT IN TUBES       19.81 (LBS)
WEIGHT IN SHELL      156.92 (LBS)
WEIGHT IN HEADER      76.07 (LBS)

                 TOTAL SYSTEM WEIGHT
                (LBS)          (TONS)

FLUID IN HX      252.80          0.1
EQUIPMENT     114955.40         51.3

TOTAL         115208.10         51.4
```

FIGURE B.9

Precooler-0.12 in. OD tubes

```
891.6599        560.0000        555.0000        608.0000        301.6399        70.0000
       4          8.0000          0.0000          0.1000          0.1200         0.1480
448.0400          0.0000               1

        FRESH WATER COOLER      EFFECTIVENESS = 0.985        HEAT LOAD (MW) = 194.43
HX MATRIX PARAMETERS

NUMBER OF UNITS =          4
NO. TUBES/UNIT =       73633
H.T. AREA/UNIT =     5917.05
LENGTH =                3.07
TUBE NPE =             4897.
SHELL NSE =           11798.
SHELL DIAMETER =       3.514
VOLUME =              111.09
OVERALL U1 =           496.5
DEL T(LM) =            63.00
TUBE VELOCITY =         3.52
TUBE MACH NC. =       0.0000
SHELL VELOCITY =      189.37
SHELL MACH NC. =      0.0483

              HEAT EXCHANGER DESIGN
DESIGN PRESSURE =    452.5      SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
TUBE ID. = 0.100 IN.      TUBE OD. = 0.120 IN.      DO/DI = 1.2000
                         (LBS)                (IN)
CORE                    13008.               0.0100
SHELL                    3386.               0.5000
TUBE SHEETS              4821.               3.6977
END CLOSURES              817.               0.2500

EQUIPMENT WEIGHT        22033. (LBS)          9.84 (TONS)          TOTAL LENGTH (FT) = 7.24

COOLANT DISCH. TEMP. (P) = 608.0          PRESSURE DROP (H) = 8.000          PRESSURE DROP (C) = 1.149

PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE = 3486.5          COOLANT PUMPING POWER (HP) =       17.
               PIPING REQUIREMENTS
               DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE       1.599       0.500          104.5                  123.9
SHELL SIDE      1.579       0.500          103.2                    0.3

              FLUID WEIGHTS

WEIGHT IN TUBES     3652.44 (LBS)
WEIGHT IN SHELL        8.77 (LBS)
WEIGHT IN HEADER   11215.00 (LBS)

               TOTAL SYSTEM WEIGHT
              (LBS)          (TONS)

FLUID IN HX    14876.21        6.6
EQUIPMENT      22032.82        9.8

TOTAL          36909.03       16.5
```

FIGURE B.10

Intercooler-0.12 in. OD tubes

```
   830.2800        560.0000        555.0000        608.0000        692.3701        70.0000
          4          4.0000          0.0000          0.1000          0.1200         0.1480
   448.0400          0.0000               1

          FRESH WATER COOLER       EFFECTIVENESS = 0.982        HEAT LOAD (MW) = 158.40
 HX MATRIX PARAMETERS

 NUMBER OF UNITS =       4
 NO. TUBES/UNIT =     64259
 H.T. AREA/UNIT =   5799.59
 LENGTH =              3.25
 TUBE NRE =           4295.
 SHELL NRE =         13117.
 SHELL DIAMETER =     3.384
 VOLUME =            116.73
 OVERALL U1 =         407.2
 DEL T(LM) =          57.25
 TUBE VELOCITY =       3.09
 TUBE MACH NO. =     0.0000
 SHELL VELOCITY =     84.79
 SHELL MACH NO. =    0.0220

              HEAT EXCHANGER DESIGN
 DESIGN PRESSURE =  1038.6      SAFETY FACTOR = 1.5      YIELD STRESS =  60000.
 TUBE ID. = 0.100 IN.      TUBE OD. = 0.120 IN.      DO/DI = 1.2000
                        (LBS)                (IN)
 CORE                  13900.               0.0100
 SHELL                  3731.               0.5000
 TUBE SHEETS            7053.               5.8357
 END CLOSURES            758.               0.2500

 EQUIPMENT WEIGHT        25343. (LBS)         11.31 (TONS)          TOTAL LENGTH (FT) = 7.64

 COOLANT DISCH. TEMP. (R) = 608.0            PRESSURE DROP (H) = 4.000            PRESSURE DROP (C) = 0.969

 PRIMARY FLOW RATE =  448.0          COOLANT FLOW RATE = 2840.4          COOLANT PUMPING POWER (HP) =        12.
                 PIPING REQUIREMENTS
                 DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
 TUBE SIDE        1.540       0.500          100.6                  114.8
 SHELL SIDE       1.520       0.500           99.4                    0.7

              FLUID WEIGHTS

 WEIGHT IN TUBES    3874.82 (LBS)
 WEIGHT IN SHELL      22.29 (LBS)
 WEIGHT IN HEADER  10009.84 (LBS)

                 TOTAL SYSTEM WEIGHT
                (LBS)          (TONS)

 FLUID IN HX    13906.95        6.2
 EQUIPMENT      25342.80       11.3

 TOTAL          39249.75       17.5
```

FIGURE B.11

Salt Water Cooler-0.25 in. OD tubes

```
   608.0000        555.0000        545.0000        576.0000          70.0000        70.0000
          2          0.0000         20.0000          0.2140           0.2500         0.3375
  6326.3980          0.0000               1

         SALT WATER COOLER       EFFECTIVENESS = 0.841          HEAT LOAD (MW) = 352.84
HX MATRIX PARAMETERS

NUMBER OF UNITS =       2
NO. TUBES/UNIT =     35665
H.T. AREA/UNIT = 45784.32
LENGTH =             22.91
TUBE NRE =          22132.
SHELL NRE =         14648.
SHELL DIAMETER =     5.577
VOLUME =           1119.65
OVERALL U1 =         695.6
DEL T(LM) =          18.91
TUBE VELOCITY =       9.55
TUBE MACH NO. =     0.0000
SHELL VELOCITY =      4.18
SHELL MACH NO. =    0.0000

               HEAT EXCHANGER DESIGN
DESIGN PRESSURE =    105.0      SAFETY FACTOR = 1.5       YIELD STRESS =  60000.
TUBE ID. = 0.214 IN.      TUBE OD. = 0.250 IN.       DO/DI = 1.1682
                         (LBS)                 (IN)
CORE                    76058.               0.0180
SHELL                   17089.               0.5000
TUBE SHEETS              6441.               3.1525
END CLOSURES             1024.               0.2500

EQUIPMENT WEIGHT        100612. (LBS)        44.92 (TONS)          TOTAL LENGTH (FT) =29.06

COOLANT DISCH. TEMP. (R) = 576.0          PRESSURE DROP (H) = 3.492           PRESSURE DROP (C) =20.000

PRIMARY FLOW RATE = 6326.9          COOLANT FLOW RATE =10816.9          COOLANT PUMPING POWER (HP) =       891.
                 PIPING REQUIREMENTS
                 DIA (FT)     T (IN)      PIPE (LBS/FT)          FLUID (LBS/FT)
TUBE SIDE         2.391       0.500         173.9                   293.2
SHELL SIDE        2.795       0.500         204.2                   378.6

               FLUID WEIGHTS

WEIGHT IN TUBES   26553.11 (LBS)
WEIGHT IN SHELL   35494.44 (LBS)
WEIGHT IN HEADER  23105.25 (LBS)

                 TOTAL SYSTEM WEIGHT
                (LBS)          (TONS)

FLUID IN HX     85152.75       38.0
EQUIPMENT      100612.30       44.9

TOTAL          185765.00       82.9
```

Appendix C

REACTOR CORE AND PRIMARY SHIELD DESIGN

C.1 Reactor Core

In Chapter 4, section 4.4, the basic approach taken to determining the reactor core size and primary shield size and weight is discussed. A "core design" from a neutronics and thermal-hydraulics standpoint was not performed. Rather as already mentioned, the annular core concept of the Westinghouse baseline was "scaled-up" to the desired power level through the use of a computer code. The power density was maintained at 262 kw/liter, and the core L/D of 0.9 was assumed. The size of the "central control island" was held constant at the value used by Westinghouse. This method of scaling is considered adequate for power levels up to about 600 MW (baseline - 300 MW) (P3).

C.2 Primary Shield

Like the reactor core, the primary shield is "scaled-up" using component thickness data from Westinghouse (P3). The shield components and their thicknesses are listed in Table C-1, for the 10 MR/HR and 1 MR/HR cases. Once the length and diameter of the reactor core is determined, shield dimensions and weights are calculated. The reactor core and shield configuration is sketched in Figure C.1. Inside the pressure vessel from top to bottom are the following components:

Component	Height
Inconel reflector	11.0 inches.
Graphite reflector	1.0 inch.
Core	L inches.
Graphite reflector	2.5 inches.
Inconel reflector	7.5 inches.
Core support plate	9.0 inches.
Plug shield (3 layers)	27.0 inches.

C.3 Computer Code SHIELD

The computer code SHIELD, written in FORTRAN IV, first sizes the core, and then calculates dimensions, volumes and weights for each of the primary shield components. The calculation is based on volumes of annular regions, and constant thickness hemispheres on the top and bottom.

Since this code is very specialized, there is only one input, defined as

Input	Description
PWR	Reactor Power (MW).

The outputs of SHIELD include, dimensions and weights of the components for two cases. The first case is the 10 MR/HR dose rate, and the second is the 1 MR/HR dose rate. Section C.3 is the code listing. Section C.4 is a sample output.

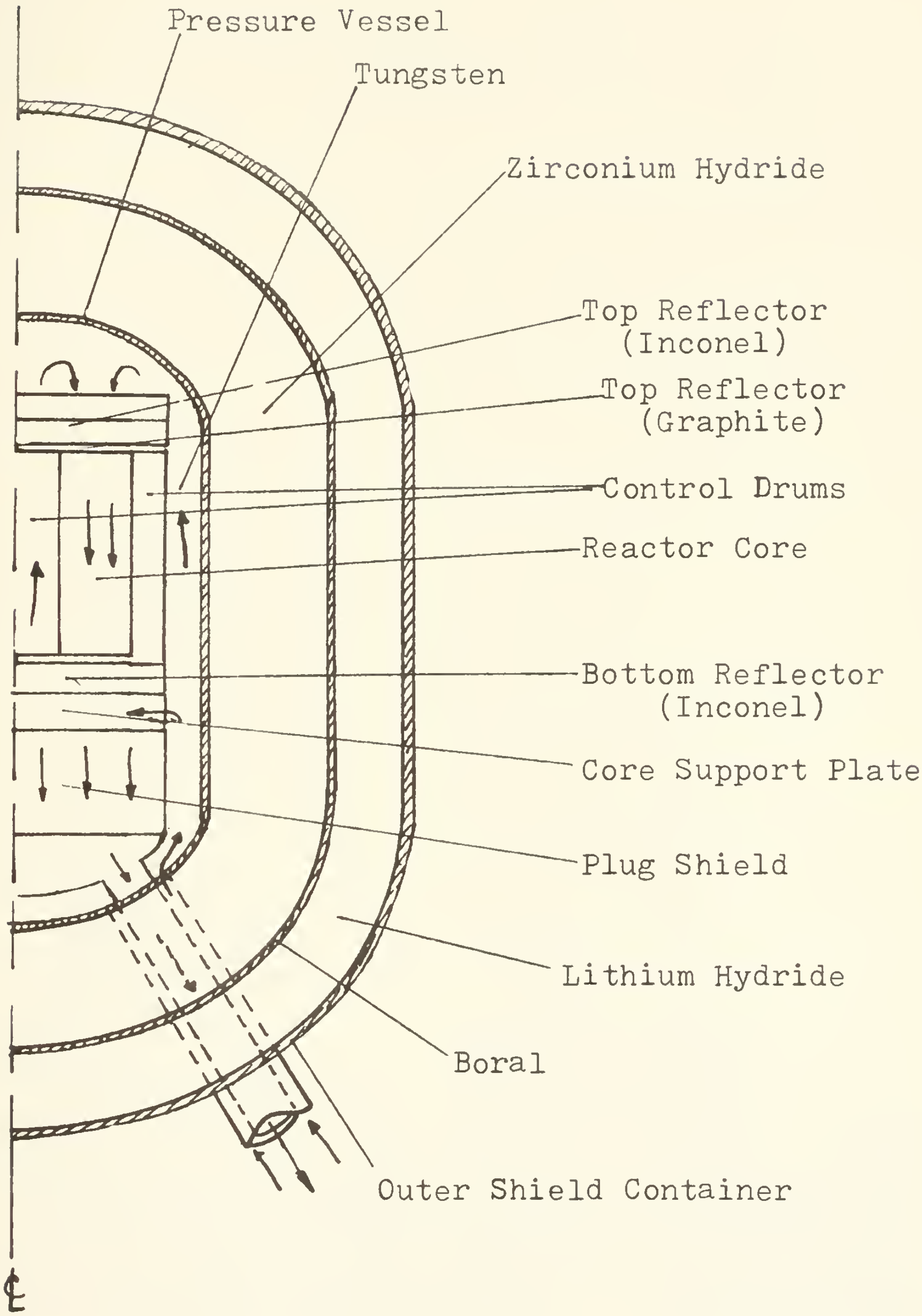
Item	10 MR/HR thickness (inches)	1 MR/HR thickness (inches)	density (lbs/m3)
Tungsten	6.925	8.075	.649
Pressure Vessel	1.5	1.5	.309
Zirconium Hydride (ZrH_2)	31.0	31.0	.191
Boral	.25	.25	---
Lithium Hydride	12.85	19.55	.027
Shield Tank	.50	.50	.309

Table C-1

PRIMARY SHIELD MATERIAL THICKNESS

FIGURE C.1

Reactor Core and Primary Shield



```
      ********************************************
      *                                          *
      *      PRIMARY SHIELD DESIGN CODE          *
      *                                          *
      ********************************************

      IMPLICIT REAL*4  (L)
      CHARACTER *8 X1 /'TUNGSTEN'/,X2*8 /'        '/
      CHARACTER *8 X3 /'PRESSURE'/, X4*8 /' VESSEL '/
      CHARACTER *8 X5 /'ZIRCONIU'/,X6*8 /'M HYD   ' /
      CHARACTER *8 X7 /'LITHIUM '/, X8*8 /'HYDRIDE ' /
      CHARACTER *8 X9 /'SHIELD T'/, X10*8 /'ANK     '/
      CHARACTER *8 X11 /'PLUG SHI'/, X12*8 /'ELD     '/
      DATA PI / 3.141593 /
    1 READ(5,10,END=30) PWR
      TW=6.925
      TLIH=12.85
   10 FORMAT(F10.2)
      LTD=.90
      DO 20 I=1,2
      V=PWR*2.32806E+02
      A0=V/(4.*PI*LTD)
      B0=SQRT(A0**2-6.56E+04)
C
C        RADIAL DIMENSIONS
C
      RCORE=(A0+B0)**(1./3.)+(A0-B0)**(1./3.)
      LCORE=2.*RCORE*LTD
      RWI=RCORE+2.65+6.+.5
      RWO=RWI+TW
      RPVI=RWO
      RPVO=RPVI+1.5
      RZRHI=RPVO
      RZRHO=RZRHI+31.
      RLIHI=RZRHO+.25
```

```
      RLIHO=RLIHI+TLIH                                                  SHLD0037
      RCNT1I=RLIHO                                                      SHLD0038
      RCNT1O=RCNT1I+.5                                                  SHLD0039
C                                                                       SHLD0040
C        AXIAL DIMENSIONS                                               SHLD0041
C                                                                       SHLD0042
      LCYL=5.5+1.+LCORE+2.5+7.5+9.+27.                                  SHLD0043
      LPVEL=RPVI/2.                                                     SHLD0044
      LPV=LCYL+2.*LPVEL+2.*1.5                                          SHLD0045
      LZRHC=LPV                                                         SHLD0046
      LZRH=LZRHC+2.*31.                                                 SHLD0047
      LLIHC=LZRHC                                                       SHLD0048
      LLIH=LZRH +2.*.25+2.*TLIH                                         SHLD0049
      LCONT1=LLIH+2.*.5                                                 SHLD0050
      LWCYLU=LCORE+6.5                                                  SHLD0051
      LWCYLL=2.5+7.5+9.                                                 SHLD0052
      LWCYLB=27.                                                        SHLD0053
      LBECYL=LWCYLL                                                     SHLD0054
      LBECLB=LWCYLB                                                     SHLD0055
      TWCYLL=4.75                                                       SHLD0056
      TWCYLB=2.5                                                        SHLD0057
      TBECYL=9.-TWCYLL                                                  SHLD0058
      TBECLB=9.-TWCYLB                                                  SHLD0059
C                                                                       SHLD0060
C        VOLUMES AND WEIGHTS                                            SHLD0061
C                                                                       SHLD0062
C              TUNGSTEN                                                 SHLD0063
C                                                                       SHLD0064
      VWCYL=PI*(RWO**2-RWI**2)*LWCYLU                                   SHLD0065
      VWCYLL=PI*((RWI-3.+TWCYLL)**2-(RWI-3.)**2)*LWCYLL                 SHLD0066
      VWCYLB=PI*((RWI-3.+TWCYLB)**2-(RWI-3.)**2)*LWCYLB                 SHLD0067
      C=2.*PI/3.                                                        SHLD0068
      VWEL1=C*RWO**2*(RWO/2.)                                           SHLD0069
      VWEL2=C*RWI**2*(RWO/2.-TW)                                        SHLD0070
      VWEL=VWEL1-VWEL2                                                  SHLD0071
      VW=VWCYL+VWCYLL+VWCYLB+VWEL                                       SHLD0072
```

```
      RHOW=.649                                                         SHLD0073
      WW=VW*RHOW                                                        SHLD0074
C                                                                       SHLD0075
C           PRESSURE VESSEL                                             SHLD0076
C                                                                       SHLD0077
      VPVCYL=PI*(RPVO**2-RPVI**2)*LPV                                   SHLD0078
      VPVEL2=VWEL1                                                      SHLD0079
      VPVEL1=C*RPVO**2*(RPVI/2.+1.5)                                    SHLD0080
      VPV=VPVCYL+2.*(VPVEL1-VPVEL2)                                     SHLD0081
      RHOPV=.309                                                        SHLD0082
      WPV=VPV*RHOPV                                                     SHLD0083
C                                                                       SHLD0084
C           ZIRCONIUM HYDRIDE (ZRH2)                                    SHLD0085
C                                                                       SHLD0086
      VZRHC=PI*(RZRHO**2-RZRHI**2)*LZRHC                                SHLD0087
      VZRHE2=VPVEL1                                                     SHLD0088
      VZRHE1=C*RZRHO**2*(RZRHI/2.+31.)                                  SHLD0089
      VZRH=VZRHC+2.*(VZRHE1-VZRHE2)                                     SHLD0090
      RHOZRH=.201                                                       SHLD0091
      WZRH=VZRH*RHOZRH                                                  SHLD0092
C                                                                       SHLD0093
C           LITHIUM HYDRIDE (LIH)                                       SHLD0094
C                                                                       SHLD0095
      VLIHC=PI*(RLIHO**2-RLIHI**2)*LLIHC                                SHLD0096
      VLIHE2=C*RLIHI**2*(RZRHI/2.+31.25)                                SHLD0097
      VLIHE1=C*RLIHO**2*(RZRHI/2.+31.25+TLIH)                           SHLD0098
      VLIH=VLIHC+2.*(VLIHE1-VLIHE2)                                     SHLD0099
      RHOLIH=.026714                                                    SHLD0100
      WLIH=VLIH*RHOLIH                                                  SHLD0101
C                                                                       SHLD0102
C           INNER CONTAINMENT (SHIELD TANK)                             SHLD0103
C                                                                       SHLD0104
      VCNTC=PI*(RCNT1O**2-RCNT1I**2)*LLIHC                              SHLD0105
      VCNTE2=VLIHE1                                                     SHLD0106
      VCNTE1=C*RCNT1O**2*(RZRHI/2.+31.25+TLIH+.5)                       SHLD0107
      VCNT=VCNTC+2.*(VCNTE1-VCNTE2)                                     SHLD0108
```

```
      WCNT=VCNT*RHOFV                                                   SHLD0109
C                                                                       SHLD0110
C                 PLUG SHIELD                                           SHLD0111
C                                                                       SHLD0112
      Q=2.*SQRT(3.)/PI-1.                                               SHLD0113
      DPS=2.*RCORE-6.                                                   SHLD0114
      DC=3.                                                             SHLD0115
      N=(DPS/DC)**2/(1.+Q)                                              SHLD0116
      NPSC=3*N                                                          SHLD0117
      WTNPSC=74.09*FLOAT(NPSC)                                          SHLD0118
      WRITE(6,100) PWR                                                  SHLD0119
  100 FORMAT('1',T5,' REACTOR POWER =',F8.2,' MW')                      SHLD0120
      J=10                                                              SHLD0121
      IF(I.EQ.2) J=1                                                    SHLD0122
      WRITE(6,101)   J                                                  SHLD0123
  101 FORMAT('0', T5,' SHIELD DESIGN ', I3,' MR/HR AT 20 FEET FROM IX CE SHLD0124
     1NTERLINE',///,T5,' ITEM',T25,' RI (IN)',T35,'RO (IN)',T45,'WEIGHT SHLD0125
     2(LBS)')                                                           SHLD0126
      WRITE(6,102) X1,X2,RWI,RWO,WW                                     SHLD0127
      WRITE(6,102) X3,X4,RPVI,RPVO,WPV                                  SHLD0128
      WRITE(6,102) X5,X6,RZRHI,RZRHO,WZRH                               SHLD0129
      WRITE(6,102) X7,X8,RLIHI,RLIHO,WLIH                               SHLD0130
      WRITE(6,102) X9,X10,RCNT1I,RCNT1O,WCNT                            SHLD0131
      WRITE(6,105) X11,X12,WTNPSC                                       SHLD0132
  102 FORMAT('0',T5,2A8,T25,F6.2,T35,F6.2,T45,F12.0)                    SHLD0133
  105 FORMAT('0',T5,2A8,T45,F12.0)                                      SHLD0134
      TWS=WW+WPV+WZRH+WLIH+WCNT+WTNPSC                                  SHLD0135
      WRITE(6,104) TWS                                                  SHLD0136
  104 FORMAT('0',T5,' TOTAL SHIELD WEIGHT =',F12.0,' (LBS)')            SHLD0137
      WRITE(6,103) LPV,LZRH,LLIH,LCONT1                                 SHLD0138
  103 FORMAT('0',T5,' OVERALL LENGTHS',//,T5,' PRESSURE VESSEL =',F6.2,'SHLD0139
     1 IN',/,T5,' ZIRCONIUM HYDRIDE =',F6.2,' IN',/,T5,' LITHIUM HYDRIDE SHLD0140
     2 =',F6.2,' IN',/,T5,' SHIELD TANK =',F6.2,' IN')                  SHLD0141
      WRITE(6,106) RCORE,LCORE                                          SHLD0142
  106 FORMAT('0',T5,' CORE DIMENSIONS',//,T5,' RADIUS =',F5.2,' IN',/,T5SHLD0143
     1,' LENGTH =',F5.2,' IN')                                          SHLD0144
```

```
      TW=8.075                                    SHLDC145
   20 TLIH=19.55                                  SHLDC146
      GC TC 1                                     SHLDC147
   30 CONTINUE                                    SHLDC148
      STCP                                        SHLDC149
      END                                         SHLDC150
```

C.5 Computer Code Shield Sample Output

REACTOR POWER = 524.85 MW

SHIELD DESIGN 1 MR/HR AT 20 FEET FROM RX CENTERLINE

ITEM	RI (IN)	RO (IN)	WEIGHT (LBS)
TUNGSTEN	38.45	46.52	144824.
PRESSURE VESSEL	46.52	48.02	30056.
ZIRCONIUM HYD	48.02	79.02	594923.
LITHIUM HYDRIDE	79.27	98.82	88121.
SHIELD TANK	98.82	99.32	30964.
PLUG SHIELD			61791.

TOTAL SHIELD WEIGHT = 950577. (LBS)

OVERALL LENGTHS

PRESSURE VESSEL =154.76 IN
ZIRCONIUM HYDRIDE =216.76 IN
LITHIUM HYDRIDE =256.36 IN
SHIELD TANK =257.36 IN

CORE DIMENSIONS

RADIUS =29.30 IN
LENGTH =52.74 IN

C.5 Computer Code Shield Sample Output (continued)

REACTOR POWER = 524.35 MW

SHIELD DESIGN 10 MR/HR AT 20 FEET FROM RX CENTERLINE

ITEM	RI (IN)	RO (IN)	WEIGHT (LBS)
TUNGSTEN	38.45	45.37	125952.
PRESSURE VESSEL	45.37	46.87	28964.
ZIRCONIUM HYD	46.87	77.87	578074.
LITHIUM HYDRIDE	78.12	90.97	53211.
SHIELD TANK	90.97	91.47	26993.
PLUG SHIELD			61791.

TOTAL SHIELD WEIGHT = 874986. (LBS)

OVERALL LENGTHS

PRESSURE VESSEL =153.61 IN
ZIRCONIUM HYDRIDE =215.61 IN
LITHIUM HYDRIDE =241.81 IN
SHIELD TANK =242.81 IN

CORE DIMENSIONS

RADIUS =29.30 IN
LENGTH =52.74 IN

Appendix D

MISCELLANEOUS CALCULATIONS

D.1 Containment

Due to the shape of the reactor pressure vessel and primary shielding, the decision was made to have a containment of similar shape (cylinder with top and bottom elliptical closures). The containment houses the reactor and primary shield, the primary heat exchangers and associated piping and the Fission Product Cleanup system.

The first step in sizing the containment is to determine the overall inside cylinder diameter. From strictly an arrangement standpoint, the containment radius is chosen to be,

$$R_c = R_{ST} + D_{PRI-Hx} + 6 \text{ ft.} \qquad (D.1)$$

For the parameters of the modified plant (1 MR/HR primary shield), R_c is 220.28 inches, or 18.36 feet. The top and bottom ellipses were chosen to have a ratio of major to minor axes of 1.35. Hence the "height" of each ellipse above the cylindrical center section was,

$$h_e = \frac{R_c}{1.35} . \qquad (D.2)$$

For this case h_e is equal to 163.17", or 13.6 feet. The overall height of the containment H_o must be equal to the height of the cylinder, plus twice the height of the ellipses,

$$H_o = H_{cyl} + 2 h_e . \qquad (D.3)$$

H_o must also be greater than the height of the primary shield

tank H_{ST},

$$H_o = H_{ST} + \Delta h. \qquad (D.4)$$

For this study Δ h is chosen to be 15.0 feet. Solving equations (D.3) and (D.4) for H_{cyl}, the cylinder height is found to be 9.1 feet.

In order to determine which design criteria is the most stringent in terms of containment pressurization, and hence containment thickness and weight, each must be considered. Based on two major criteria 1) pipe rupture inside containment - containment pressurization and 2) containment sinks - maximum depth is 1000 ft, the latter was found to determine the containment thickness.

The pipe rupture case, expands a gas initially at a pressure of about 1600 psia into a volume (based on component volumes) that is approximately 18 times the original primary system volume. This increases the containment pressure to roughly 100 psia assuming it was initially at 1 atmosphere. This assumes no additional heating of the gas to increase the pressure.

The second case, submergence to 1000 ft requires the containment to withstand hydrostatic pressures of about 660 psia. This is clearly greater than the first case. The cylinder was sized using the same formula as used in HXSIZE to determine Hx equipment shells,

$$t_{cyl} = \frac{P_D D_s}{2\sigma} . \qquad (D.5)$$

Again a factor of safety of 1.5 was applied to the hydrostatic pressure to obtain the design pressure, P_D. The value of yield strength chosen is 50,000 psi. The resulting cylinder thickness is about 3 inches. Using a density of .309 lbs/in3, the corresponding cylinder weight is about 139,000 lbs.

The elliptical top and bottom caps are assumed to be 1.5 inches thick or,

$$t_{EL} = \frac{P_D \; D_S}{4 \, \sigma} \; . \tag{D.6}$$

The corresponding total weight of the top and bottom ellipses is about 232,000 lbs. The total containment weight is then the sum of the two portions, or

$$W_{CONT} = 139{,}000 + 232{,}000 = 371{,}000 \text{ lbs.}$$

D.2 <u>Scaling Westinghouse Weight Data</u>

Data from Westinghouse was available for two power plant levels, 140,000 and 225,000 SHP. In the range of interest, the plot of specific propulsion plant weight versus shaft horsepower (Figure 3.9), was essentially a straight line on log-log paper. It was therfore assumed that the individual components would follow a power law relationship such as,

$$W_i = A_i \left(\frac{SHP}{1000}\right)^{B_i} \; . \tag{D.7}$$

Taking the logarithm of both sides one obtains

$$\log W_i = \log A_i + B_i \log\left(\frac{SHP}{1000}\right) , \tag{D.8}$$

which is in the form,

$$Y = A + BX \; . \tag{D.9}$$

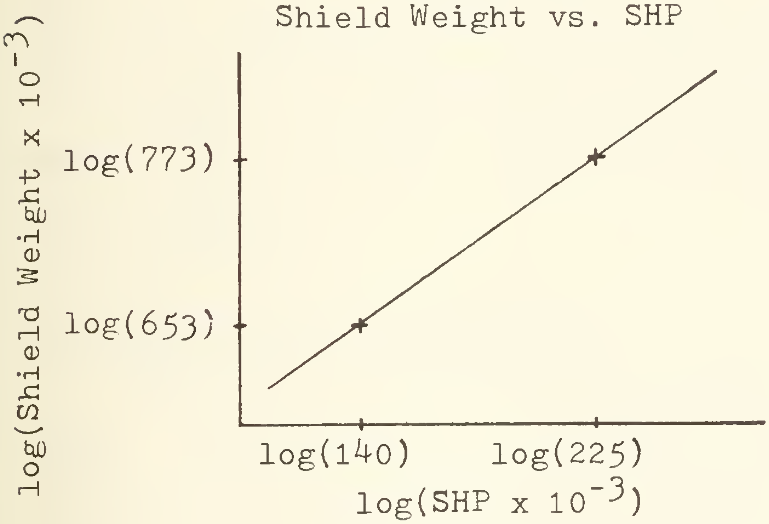
Since two data points were available for each of the individual components of Table 5-7, the Ai and Bi could be determined.

As an example, consider the Shield weights for both the 140K SHP and 225K SHP plants at a dose rate of 10 MR/HR,

Power level (SHP)	Weight (lbs x 10^{-3})
140,000	653.
225,000	773.

Figure D.1 is a log-log plot of these points indicating a straight line between them.

FIGURE D.1
Shield Weight vs. SHP



The slope B is given by

$$B = \frac{\log 773 - \log 653}{\log 225 - \log 140} = 0.356. \qquad (D.10)$$

The "intercept", log A can be determined from either point, i.e.,

$$\log A = \log (W) - B \log\left(\frac{SHP}{1000}\right) . \qquad (D.11)$$

Here A is 112.6, and the resulting expression for the primary shield weight is,

$$W_{SHIELD} = 112.6 \times 10^3 \left(\frac{SHP}{1000} \right)^{.356} . \qquad (D.12)$$

In a similar manner the weights for the other items in Table 5-1 can be determined. The resulting equations for the Westinghouse design are given in Table D-1. The relationships derived in Table D-1 are developed by the author, based on data supplied by WANL (T1 , T2). These equations, when summed, for a given power levle give results that fall on the line of Figure 3.9 . Although the sum of the parts equals the whole, the individual parts may not be the same as Westinghouse calculations. For the range of power levels considered here, the above approach was thought to be adequate.

D.3 Piping and Fluid Weights

Detailed calculations of the weights of piping and fluids is not entirely feasible. Instead estimates of the weights are made here, based on, 1) the weights/foot of piping from HXSIZE for the individual components, 2) estimates of piping lengths from the sketches in Figures 5.3a and 5.3b. The results are tabulated in Table D-2. The total is approximately 230,000 lbs, and may be conservative. In order to take into account uncertainties in this figure, the weights of valves, auxiliaries, and control systems, a final "Water and Auxiliary systems" weight of 400,000 lbs has been chosen.

ITEM	WEIGHT (1000 lbs) 10 MR/HR	1 MR/HR
Reactor	$.181 \left(\frac{SHP}{1000}\right)^{.931}$	Same
Shield	$112.6 \left(\frac{SHP}{1000}\right)^{.356}$	$133.2 \left(\frac{SHP}{1000}\right)^{.356}$
T-C-Hx	$7.24 \left(\frac{SHP}{1000}\right)^{.57}$	Same
Control Gas Storage	$2.46 \left(\frac{SHP}{1000}\right)^{.549}$	Same
Emergency Cooling	$.15 \left(\frac{SHP}{1000}\right)^{.709}$	Same
Helium	$1.0 \left(\frac{SHP}{140x10^3}\right)$	Same
Equipment Shield	$46.64 \left(\frac{SHP}{1000}\right)^{.440}$	$65.48 \left(\frac{SHP}{1000}\right)^{.440}$
Fission Product Cleanup	$4.13 \left(\frac{SHP}{1000}\right)^{.44}$	Same
Water and Auxiliaries	$.575 \left(\frac{SHP}{1000}\right)^{1.147}$	Same
Power Transmission	$15.54 \left(\frac{SHP}{1000}\right)^{.513}$	Same

Table D-1

ASSUMED REFERENCE BASELINE WEIGHT EQUATIONS

	Weight/ft pipe	wt/ft fluid	total wt/ft	total length	total weight
PRI-HX					
tube side	256.2	.7	256.9	~40 ft	10,276
shell side	372.5	5.7	378.2	~40 ft	15,128
FPC	256.2	.7	256.9	~40 ft	10,276
Recuperator					
tube side	249.8	.7	250.5	~15 ft	3,758
shell side	344.2	5.3	349.5	~50 ft	17,475
Precooler					
tube side	106.9	129.5	236.4	~100 ft	23,640
shell side	102.7	.3	103.0	~20 ft	2,060
Intercooler					
tube side	102.9	120.0	222.9	~100 ft	22,290
shell side	98.9	.7	99.6	~25 ft	2,490
Primary He pipe					
inside	372.5	5.7	378.2	~100 ft	37,820
outside	372.5	5.7	378.2	~100 ft	37,820
HPT - LPT crossover	100.	5.	105.	~25 ft	2,625
Salt water	173.5	281.8	455.3	~100 ft	45,530
					231,188 lbs.

Table D-2

PIPING AND FLUID WEIGHT ESTIMATE

This leaves a margin of 170,000 lbs for the above listed items, in the final weight summary given in Table 5-6.

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M27717 Mahoney
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